Chapter 9

Urban Stormwater and Watershed Management: A Case Study

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Overview

Interest in watershed management has waxed and waned over the past century. The concept of integrated water and land management was first articulated in the western U.S. by John Wesley Powell in a report to the Congress in 1878 (Peterson 1984). However, Congress rejected his idea and continued to use an ad hoc approach to authorizing projects. During the 20th century, interest in watershed planning has come and gone several times. Following World War I, unified planning at the river basin scale flourished with major studies and implementation on numerous river basins, (e.g., the creation of the Tennessee Valley Authority). The National Resources Planning Board provided the leadership for these efforts (Viessman and Welty 1985). Increased environmental awareness during the 1960's and 1970's led to expanded efforts to evaluate water quality and related problems on a regional level. During the 1980's, primary reliance was placed on a command and control approach for addressing water resources problems. A strong move back to the watershed management approach began a few years ago, (e.g., see the Proceedings of Watershed 93 and Watershed 96, WEF, 1993, 1996). While it is axiomatic that integrated, holistic, sustainable infrastructure systems are very desirable, demonstrated success stories of how such systems might function effectively are rare (Heaney 1993).

Watershed Planning Methodologies

Early watershed planning efforts focused on developing "master plans" which, once approved, would serve as a blueprint for management in the basin. Prior to computers, such efforts faced severe technological limitations in bringing together large amounts of information and analyzing alternatives in a systematic manner. The widespread availability of mainframe computers in the 1960's and associated computer-based simulation and optimization techniques led to large-scale efforts to develop "rational" master plans (Maass et al. 1962). Integrated river basin planning models were developed as early as 1971. An updated summary of these quantitative methodologies is contained in Mays and Tung (1992) and Wurbs (1994). The thrust in developing better planning methodologies was in devising ever-more complex models, (e.g., three dimensional lake models, nonlinear programming models). Unfortunately, the sophistication of the models greatly outstripped the availability of data. Nevertheless, models have had a strong positive influence in water resources planning (Office of Technology Assessment 1982).

Dissatisfaction with rational planning models and major improvements in metrology led to the more recent shift to data rather than model driven approaches wherein the analyst attempts to match the models with the data. These information driven approaches are often classified as Decision Support Systems (DSS) (Loucks 1995). Contemporary DSS's contain a mixture of simulation and optimization models, databases, geographical information systems, typically with a graphics front-end to integrate these systems. The DSS should incorporate real-time control systems if they have been installed. The DSS is more than a series of interfaced programs. It also embodies a different philosophy of planning. Rather than focusing on "solving" the "problem", the DSS provides an operational framework in which continuous process improvement is stressed.

Contemporary Principles of Watershed Management

During recent years, several national and regional groups have articulated new principles of water and environmental management. A summary of these positions follows.

American Water Resources Association

The American Water Resources Association (AWRA) represents the largest collection of professionals dealing with water resources problems. They published the following list of seven guiding principles of water resources management (Anonymous 1992):

1. Water problems should be approached in a holistic way with the watershed as the basic planning unit; and the water requirements of natural systems within the watershed must be fully integrated into water-management decisions.

2. The framework for policy making must be flexible and adaptive to changing conditions, needs, and values, yet provide a level of predictability and timeliness needed to support management and investment decisions; management strategies must focus on appropriate geography to effectively deal with the problems at hand; and the public must understand the nature of the problems and how resource managers intend to solve them.

3. The States play a key role in water management and should be delegated responsibility for specific water-related Federal programs; authority and accountability should be decentralized to the lowest capable level of government while ensuring oversight and enforcement of these programs; obstacles to meaningful intergovernmental partnerships, such as overlapping missions, jurisdictional boundaries, and responsibilities, must be overcome.

4. Water policy development should express a preference for negotiation, market-like approaches, and performance standards and should include more consultation, cooperation, and concurrence between all levels of government and non-governmental entities with interests in the policies.

5. Federal, State, and local participation should be encouraged in the development of each other's program policy development, implementation, and administration; more leadership capacity needs to be developed among politicians, water professionals, and the public to champion concerns and reforms.

6. Freshwater is a fundamental integrating ingredient in natural resources management and an essential building block for a competitive and healthy economy.

7. The goal of freshwater sustainability should be a guiding principle for future water-resource management.

Water Environment Federation

The WEF is the professional organization, which represents the water quality field. They have been conducting a major initiative called Water Quality 2000. The output of the third phase of their effort is the result of an 18-month consensus process that included more than 100 experts representing a wide variety of interests. This report calls for a national water policy that will improve protection of surface and ground waters by combining the following three interrelated strategies (WEF 1993):

1. Pollution prevention.
2. Increased individual and collective responsibility for protecting water resources.
3. Reorientation of water research programs and institutions along natural watershed boundaries.

U.S. Environmental Protection Agency

The U.S. EPA has adopted a watershed approach to water quality management (US EPA, 1991). This posture represents a revisiting of their earlier leanings in this direction.

Case Study of Urban Stormwater Management within a Watershed Framework

Introduction

The benefits and challenges of using an integrated, watershed-based approach to water and environmental management can be demonstrated using a case study with meaningful data and models. BCW, which includes the City of Boulder, was selected for this purpose. A map of BCW is shown in Figure 9-1. BCW is a textbook watershed with its origins in the Rocky Mountains from where it flows out of the mountains through the Front Range of Colorado.

With the beginning of mining in 1858, the water and land associated with development activities have had a significant impact on BCW. The initial mining activities altered streamflows, greatly increased erosion and pollution, and forever altered the "natural" hydrology. From 1858 to the present, BCW has been drastically altered by activities such as mining, urbanization, agricultural activities, and hydropower development. BCW suffered serious stormwater pollution from mining activities beginning in the 1860s. Thus, nonpoint pollution is an old problem in BCW.

BCW has also been adapted to provide water supply, flood control, recreation, and instream flow needs. These interventions are both structural and nonstructural. Structural interventions include construction of reservoirs, canals, pipelines, pump stations, hydropower generation, water and wastewater collection and treatment systems, flood control levees, instream and wetland restoration, and imports and exports of water. Nonstructural interventions include flood warning systems, floodplain management, water rights enforcement, water conservation programs, and education about watershed protection.

The end result of all of these interventions is a complex watershed system, which has been adapted to serve the needs of society as well as the natural system. This level of development and adaptation is typical of watersheds in the U.S. and other developed areas. Dealing with the watershed as a system is essential in contrast with trying to isolate one component of it and assume away all of the complexity that is associated with this system. While the focus of this report is urban stormwater quality management, these other considerations should also be kept in mind. The components of BCW are discussed in the following sections.

Hydrology

Introduction

BCW can be partitioned into three main sources: North Boulder Creek, Middle Boulder Creek, and South Boulder Creek, as shown in Figure 9-1. According to WBLA, Inc. (1988), the general water budget for the system inflows, under natural conditions, is as follows:

Source	Percent of Total
North Boulder Creek	20
Middle Boulder Creek	30
South Boulder Creek	40
Other Tributaries	10
Total	100

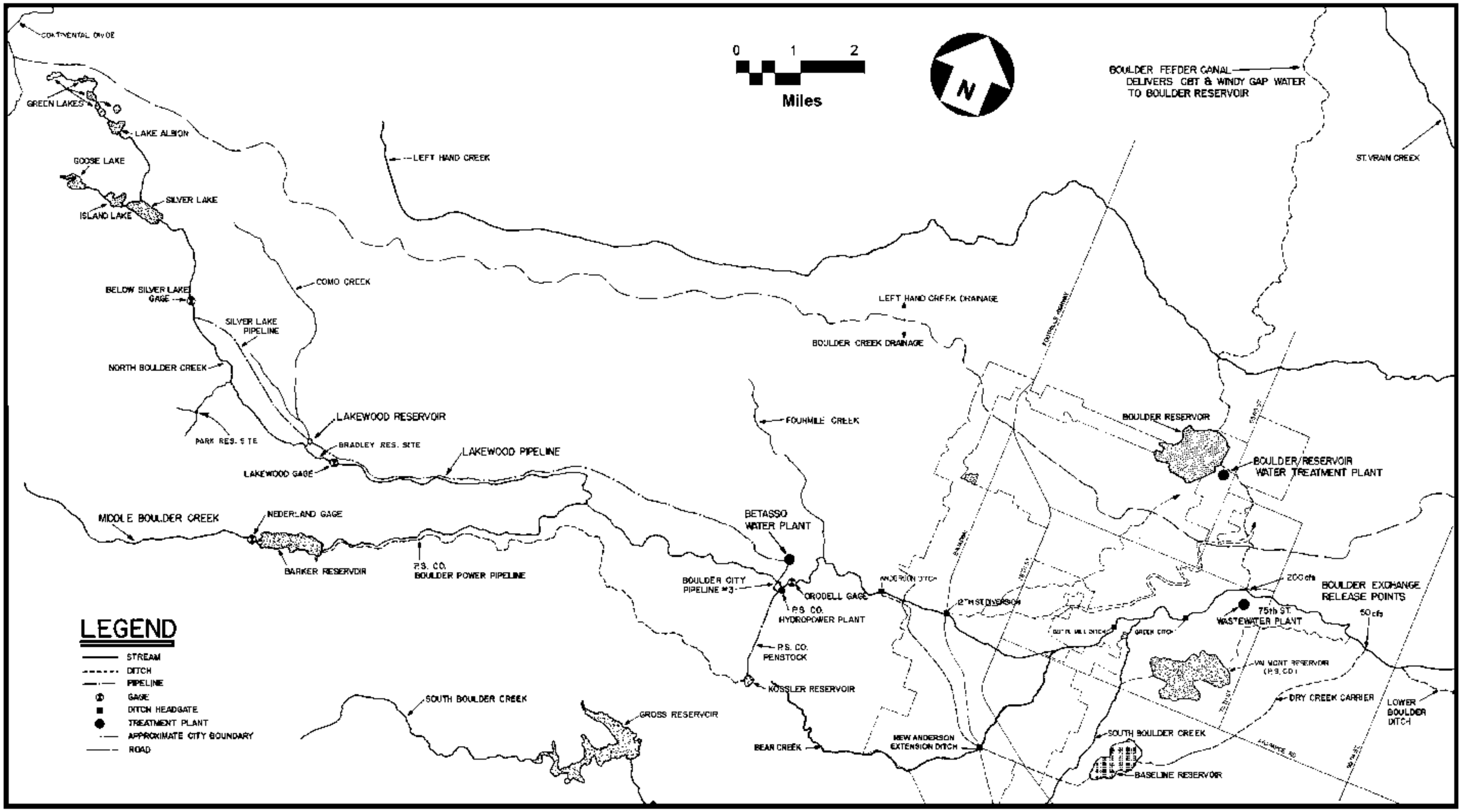

Figure 9-1. Boulder Creek Watershed, CO. City of Boulder 1998. (Reprinted Courtesy of Hydrosphere)

The total estimated natural inflow averaged 140,000 acre feet per year. The natural inflow is estimated by correcting the observed historical inflows for development activities such as storage, imports, and exports. The reconstructed expected natural inflows of Boulder Creek at Broadway, which is located at the upstream end of the City of Boulder, are shown in Table 9-1 and Figure 9-2.

The natural inflow averages 108 cfs. Depletions have reduced this natural flow to an average of 52 cfs, or 48% of the natural inflow. The monthly pattern of inflows, shown in Table 9-1 and Figure 9-2, indicates the dominant influence of the spring runoff in supplying water to the downstream portion of BCW. About 72 % of the annual runoff occurs during May, June, and July. The traditional low flow period of concern for water quality management occurs in late summer when the stream temperatures are high and flow in the receiving water is low. The lowest historical flows occur in October at the end of the irrigation season as shown in Table 9-1. The average flow at Broadway in October is 10 cfs. However, these inflows at Broadway do not necessarily pass through the city. Much of this inflow is diverted between Broadway and 75th St., the downstream end of the City of Boulder.

Table 9-1. Boulder Creek watershed streamflows on Main Boulder Creek below Broadway in Boulder, CO (WBLA Associates 1988).

Month	Natural (cfs)	Historical (cfs)	Natural (%)	Historical (%)
January	15	33	1.2	2.5
February	18	33	1.4	2.5
March	22	22	1.7	1.7
April	58	35	4.5	2.7
May	250	115	19.3	8.9
June	435	180	33.5	13.9
July	252	90	19.4	6.9
August	105	25	8.1	1.9
September	52	20	4.0	1.5
October	40	10	3.1	0.8
November	30	25	2.3	1.9
December	20	35	1.5	2.7
Avg.	**108**	**52**	**100**	**48.0**

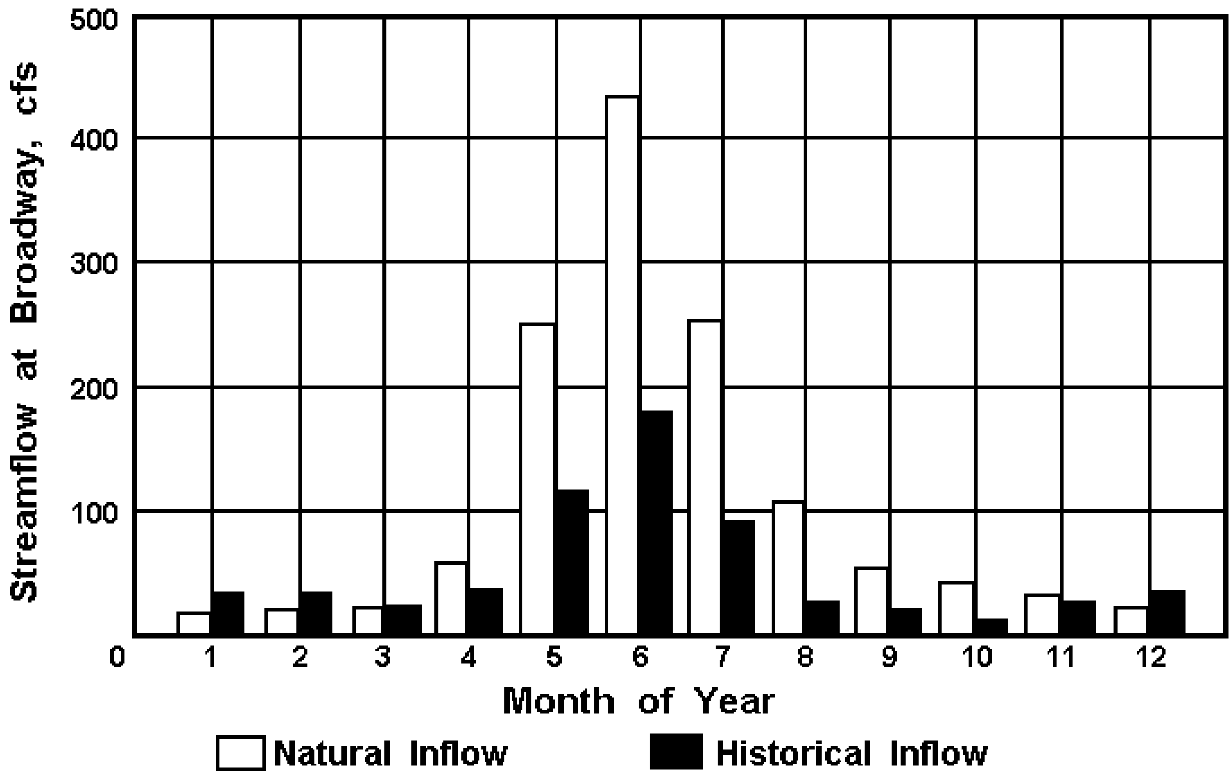

Figure 9-2. Monthly inflows of Boulder Creek to Boulder, CO.

Precipitation Analysis

The average annual precipitation in Boulder is 18.2 inches with about two thirds of this occurring between April and September. Total annual precipitation has ranged from 10 to 28 inches. Annual and monthly total precipitation data are presented in Figures 9-3 and 9-4 and Table 9-2. May is the wettest month of the year.

Storm event statistics were tabulated using NWS hourly rainfall data. A storm event is defined as ending when it hasn't rained for six consecutive hours. An estimated minimum storm event precipitation of 0.15 inches is needed to initiate runoff. The relative frequency distribution for these runoff producing events (RPE) is shown in Figure 9-5. An average of 29.27 RPEs occur per year. The monthly distributions of storm events is shown in Table 9-3 and Figures 9-6 to 9-9. An average of 2.44 RPEs occur per month with as little as 1.3 RPEs in January to a high of 3.6 RPEs in May. The average RPE volume/month is 1.25 inches. The mean volume per RPE is 0.49 inches. The mean event duration is 5.8 hours and the mean interevent time is 318 hours. Overall, RPEs occur less than 2% of the year. For Boulder, the precipitation falling from November to March is typically occurs as snow.

Streamflow Stations

A summary of available stream gauging stations is presented in Table 9.4. A brief summary of the individual watersheds and stream gauging stations follows.

North Boulder Creek

The flows in North Boulder Creek are directly affected by seven city owned reservoirs with a total storage capacity of about 7,000 acre feet (WBLA 1988). The City diverts water from North Boulder Creek via the Silver Lake and Lakewood pipelines. Natural flows at Lakewood average 21,800 acre feet per year over about 31 square miles of drainage or about 0.97 cfs/mi^2. As shown in Table 9-1, development has had a major impact on North Boulder Creek with a combination of storage and direct diversions. The natural flow below Lakewood of 31.25 cfs has been reduced by about one third due to man's activities with no flow in the stream during the colder months of the year. No long-term stream gauging stations exist for North Boulder Creek. The only available record is a few years of data on the upper parts of the North Boulder Creek Watershed. Flows in North Boulder Creek are affected by upstream storage and a major diversion of water for the City of Boulder's water supply system via the Lakewood pipeline. Natural flows for North Boulder Creek can be estimated based on its hydrologic similarity to Middle Boulder Creek above Nederland.

Middle Boulder Creek

According to WBLA (1988), Middle Boulder Creek flows essentially undisturbed into Barker Reservoir at Nederland. The average runoff is about 1.55 cfs/mi^2. Barker Dam and associated diversions for water supply and hydropower exert a drastic influence on Middle Boulder Creek downstream of Barker Dam. The City diverts water for water supply and Public Service Company of Colorado diverts water for hydropower, both via the Barker pipeline. As shown in Table 9-1, the natural outflow has decreased from about 108 cfs to less than 52 cfs, a loss of over half of the natural flow in the stream. With current diversions, only about one or two cfs of flow reach the confluence of North Boulder Creek and Middle Boulder Creek during the colder months of the year.

The flows of Middle Boulder Creek as it enters the City are dominated by PSCO hydropower releases and diversions by a large number of agricultural ditches. Historically, during dry years, extended periods of flows less than one cfs have been experienced below Broadway due to agricultural diversions and Boulder's exchange operations (WBLA 1988). Winter flows fluctuate wildly due to hydropower releases with flows ranging from 2 to 140 cfs over a single day as shown in Figure 9-10.

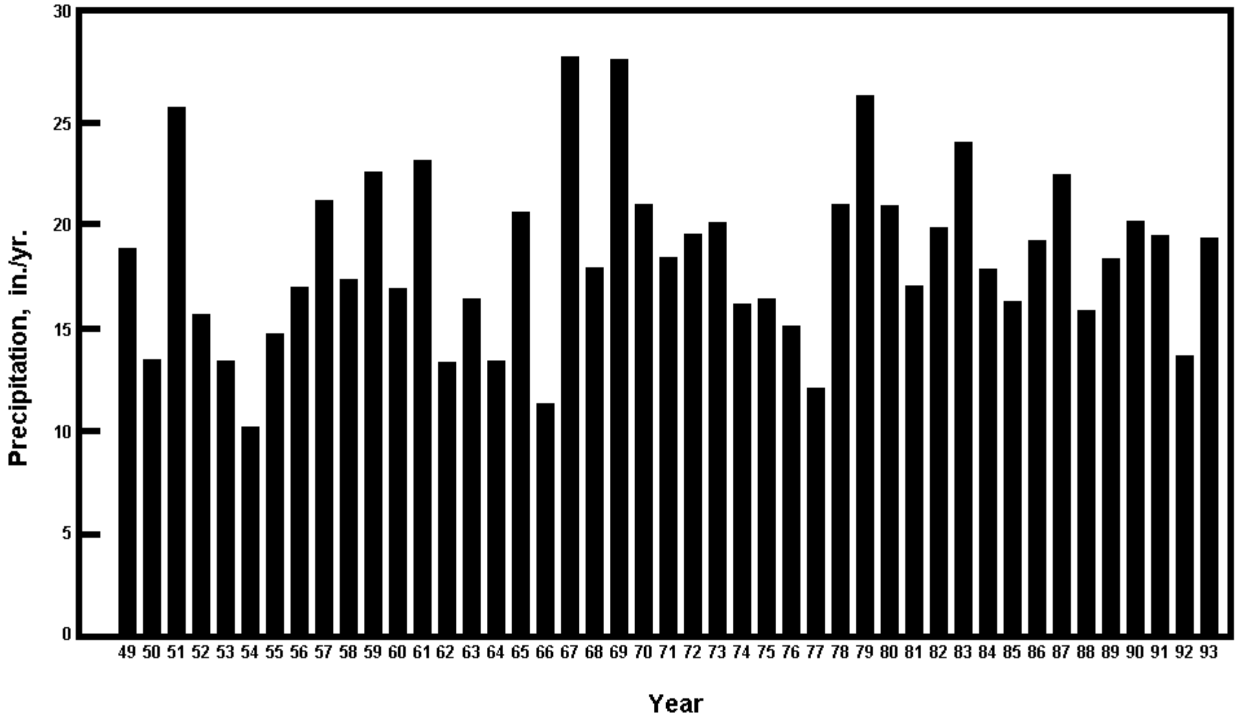

Figure 9-3. Mean annual precipitation in Boulder, CO.

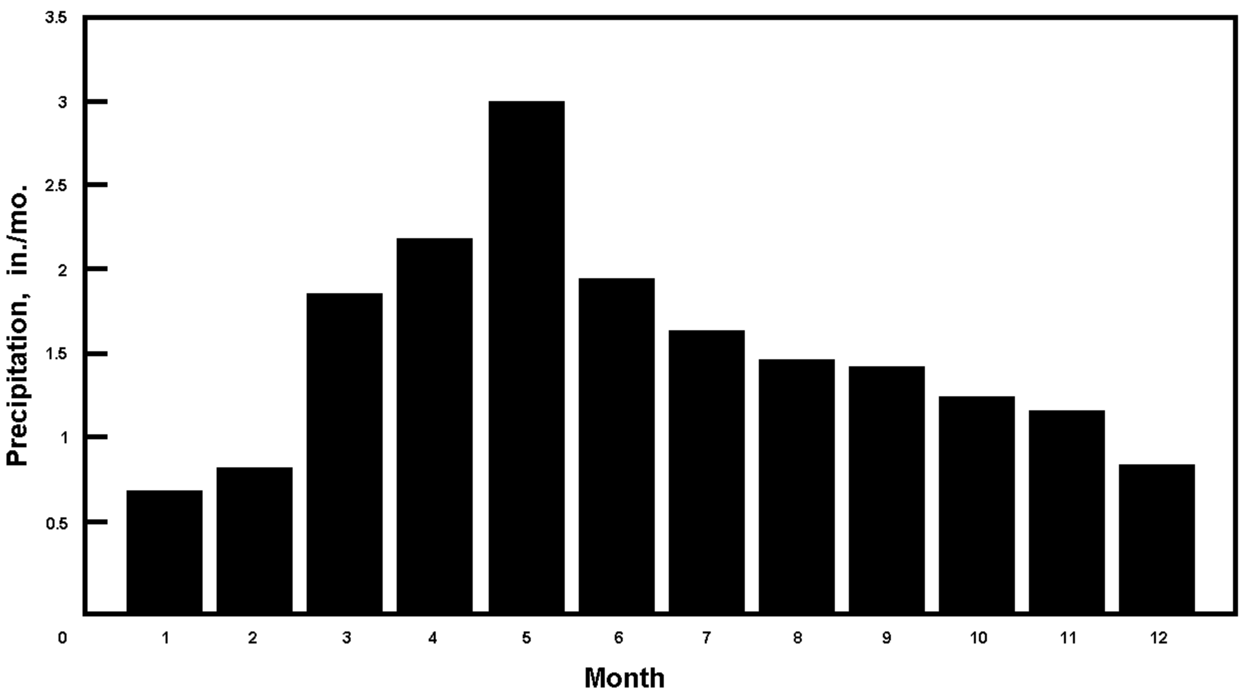

Figure 9-4. Mean monthly precipitation in Boulder, CO.

Table 9-2. Monthly precipitation in Boulder, CO, 1949-1993.

	Month												
Yr.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
49	0.52	0.10	2.47	2.12	3.28	7.03	1.05	0.31	0.00	1.49	0.00	0.27	18.6
50	0.92	0.24	0.34	2.74	3.07	0.72	1.47	0.19	1.30	0.38	1.79	0.27	13.4
51	0.67	0.93	1.97	2.23	2.01	2.09	1.16	8.59	0.88	2.62	1.12	1.40	25.7
52	0.03	0.39	1.71	2.84	3.73	0.93	0.64	3.47	0.29	0.24	1.29	0.00	15.6
53	0.22	0.66	1.60	2.18	2.13	0.76	2.26	0.92	0.00	0.51	1.03	1.04	13.3
54	0.57	0.20	1.28	0.88	1.08	0.97	1.79	0.44	1.31	0.34	0.64	0.65	10.2
55	0.32	1.27	2.03	0.20	2.25	1.99	0.85	2.25	0.80	0.37	1.42	0.90	14.7
56	0.24	1.70	1.30	1.44	2.85	2.00	2.78	1.53	0.00	0.48	1.83	0.71	16.9
57	0.85	0.99	0.56	3.12	8.61	0.46	0.73	2.35	0.80	1.86	0.69	0.06	21.1
58	0.70	0.35	2.88	2.74	3.91	1.38	1.35	0.67	0.74	0.61	0.99	0.88	17.2
59	1.37	1.59	2.65	3.71	3.62	0.51	0.56	1.02	3.39	2.66	1.12	0.14	22.3
60	0.68	1.81	1.13	2.13	3.68	0.52	0.94	0.26	0.52	2.76	0.66	1.71	16.8
61	0.75	1.04	3.48	1.39	3.37	2.11	1.69	1.65	4.47	1.25	1.13	0.69	23.0
62	1.87	1.15	0.64	0.90	2.06	2.49	1.45	0.21	0.24	1.27	0.70	0.17	13.2
63	1.00	0.53	2.45	0.17	1.05	4.58	0.46	1.84	2.35	0.35	0.72	0.83	16.3
64	0.39	0.96	1.59	1.41	2.06	1.58	2.20	0.31	0.34	0.22	1.17	1.00	13.2
65	1.11	1.73	2.10	2.38	1.34	2.55	4.81	0.33	3.00	0.24	0.25	0.66	20.5
66	0.21	1.27	0.26	1.44	0.70	1.27	0.90	0.45	2.94	0.79	0.60	0.30	11.1
67	0.84	0.61	1.29	1.90	5.00	4.83	2.81	4.94	0.92	1.29	1.46	2.07	28.0
68	0.20	1.20	0.86	2.27	2.33	2.54	1.30	3.84	1.26	0.47	0.81	0.65	17.7
69	0.36	0.35	1.01	1.05	8.51	5.24	2.33	0.46	0.47	6.36	0.96	0.72	27.8
70	0.15	0.82	5.72	1.25	1.07	2.68	1.34	0.17	4.31	1.25	1.50	0.50	20.8
71	0.70	2.10	1.10	5.40	1.00	0.10	1.00	0.20	4.30	0.90	0.80	0.60	18.2
72	1.40	0.70	1.00	1.30	2.99	2.30	2.40	1.20	1.00	1.30	2.50	1.30	19.4
73	1.40	0.20	1.70	5.50	4.00	0.50	1.10	0.20	1.43	0.70	1.70	1.40	19.8
74	1.00	1.20	1.50	2.70	0.00	2.40	0.80	0.60	1.90	2.10	1.30	0.50	16.0
75	0.50	1.10	2.00	2.80	2.99	1.60	0.40	0.90	1.00	0.80	1.40	0.70	16.2
76	0.60	0.40	1.60	2.10	1.40	1.20	1.80	1.10	2.80	1.20	0.30	0.40	14.9
77	0.20	0.70	0.50	3.10	0.60	0.50	3.10	1.90	0.20	0.30	0.50	0.20	11.8
78	0.80	0.40	1.60	3.00	7.00	1.11	1.00	1.30	0.10	2.10	0.20	2.10	20.7
79	0.70	0.30	2.70	2.10	5.40	3.00	0.70	3.90	0.50	1.30	3.00	2.40	26.0
80	1.50	1.00	2.60	5.50	3.80	0.20	1.70	1.10	1.20	0.80	1.10	0.20	20.7
81	0.20	0.40	2.30	1.30	4.80	1.50	1.70	1.10	0.80	1.20	0.30	1.20	16.8
82	0.20	0.82	0.60	0.50	4.50	2.20	4.60	1.50	1.43	1.20	0.40	1.60	19.5
83	0.20	0.10	4.70	3.00	4.70	2.30	2.60	0.80	0.30	0.20	3.90	0.90	23.7
84	0.50	0.90	2.60	0.00	2.80	1.60	1.60	2.00	0.90	4.00	0.00	0.60	17.5
85	0.70	1.00	1.40	1.90	1.20	1.80	1.90	0.00	2.50	0.90	1.70	1.00	16.0
86	0.10	1.00	0.60	4.80	2.50	1.50	1.70	0.20	0.80	3.40	1.90	0.50	19.0
87	1.10	0.82	2.20	2.30	1.80	5.70	1.10	1.80	1.00	0.80	1.70	1.90	22.2
88	0.40	1.10	2.40	1.40	3.40	0.60	0.50	1.20	1.90	0.10	0.70	1.80	15.5
89	0.70	1.00	0.90	1.80	3.00	2.10	1.30	1.40	2.90	1.20	0.30	1.50	18.1
90	0.90	0.70	4.40	2.20	1.70	0.20	3.20	1.80	1.80	0.80	1.40	0.80	19.9
91	1.00	0.10	0.50	2.00	4.10	1.80	2.70	1.50	1.50	0.80	3.20	0.00	19.2
92	0.70	0.00	3.40	0.50	1.90	1.00	1.10	3.20	0.00	0.40	0.30	0.86	13.4
93	0.67	0.82	1.40	2.10	1.20	2.90	0.70	0.60	3.70	2.22	2.20	0.60	19.1
Mean	0.67	0.82	1.84	2.17	2.99	1.94	1.63	1.46	1.43	1.26	1.17	0.86	18.24
Max.	1.84	2.10	5.72	5.50	8.61	7.03	4.81	8.59	4.47	6.36	3.90	2.40	28.00
Min.	0.03	0.00	0.26	0.00	0.00	0.10	0.40	0.00	0.00	0.10	0.00	0.00	10.20
STD	0.42	0.49	1.16	1.29	1.87	1.50	0.99	1.55	1.24	1.17	0.83	0.60	4.15
C of V	0.62	0.60	0.63	0.59	0.63	0.77	0.61	1.06	0.87	0.93	0.71	0.69	0.23

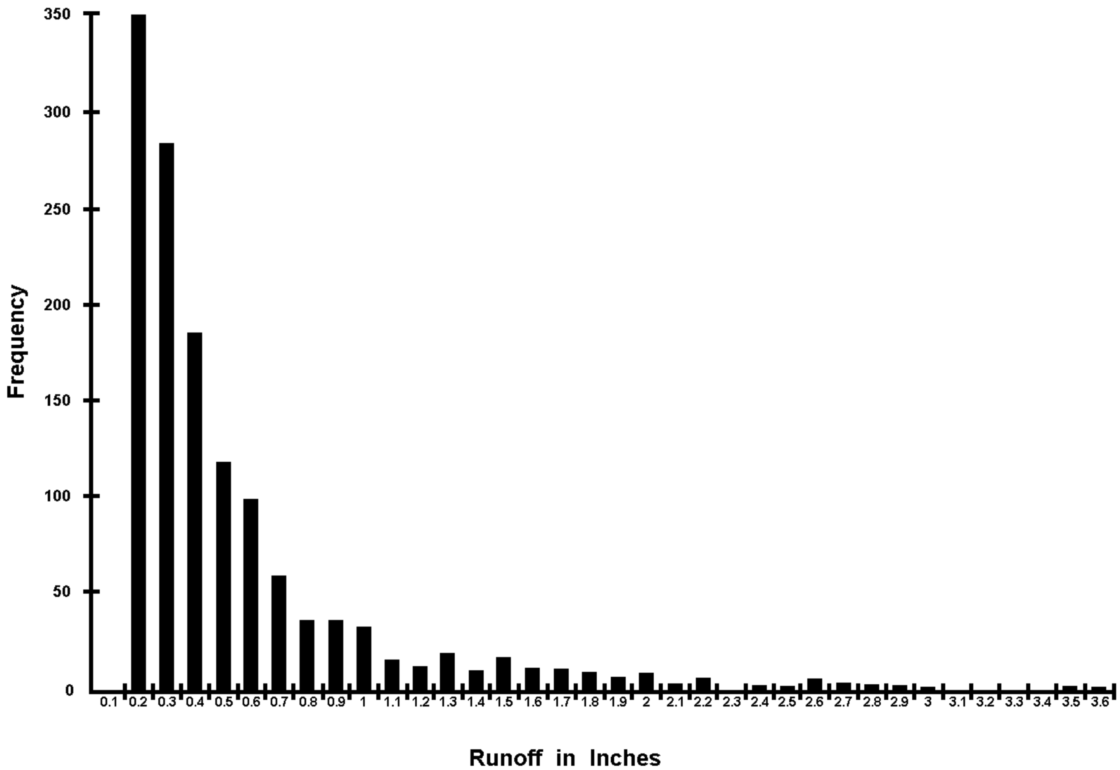

Figure 9-5. Relative frequency for runoff producing events in Boulder, CO.

Table 9-3. Summary of monthly and annual storm event statistics for Boulder, CO 1949-1993.

		Volume				Duration			Interevent Time		
Month	Events/mo.	Average (in./mo.)	Mean (in./event)	STD (in./event	C of V	Mean (hours)	STD (hours)	C of V	Mean (hours)	STD (hours)	C of V
Jan	1.31	0.49	0.372	0.216	0.58	6.68	5.212	0.781	546	455	0.834
Feb	1.47	0.60	0.407	0.210	0.52	6.68	6.885	1.031	462	444	0.961
Mar	3.13	1.54	0.490	0.414	0.85	6.04	6.460	1.070	319	428	1.341
Apr	3.20	1.84	0.574	0.482	0.84	6.69	5.308	0.794	206	179	0.872
May	3.58	2.48	0.693	0.822	1.19	7.71	9.192	1.192	211	263	1.248
Jun	2.84	1.68	0.592	0.612	1.03	5.70	6.125	1.074	199	231	1.162
July	3.16	1.36	0.432	0.376	0.87	3.20	2.421	0.757	271	270	0.999
Aug	2.31	1.15	0.496	0.526	1.06	3.31	2.718	0.822	244	258	1.058
Sep	2.33	1.16	0.497	0.434	0.87	5.67	5.445	0.961	295	303	1.029
Oct	2.11	1.06	0.500	0.442	0.88	6.00	5.696	0.949	388	425	1.095
Nov	2.16	0.98	0.454	0.302	0.67	6.33	5.264	0.832	320	371	1.158
Dec	1.67	0.65	0.387	0.253	0.65	6.08	5.253	0.864	362	288	0.795
Total	29.27	14.97									
Average	2.44	1.25	0.49	0.42	0.83	5.84	5.50	0.93	318.48	326.32	1.05

Notes: Annual statistics based on total data set, not averages of monthly means.

An event is defined as ending when six dry hours have elapsed.

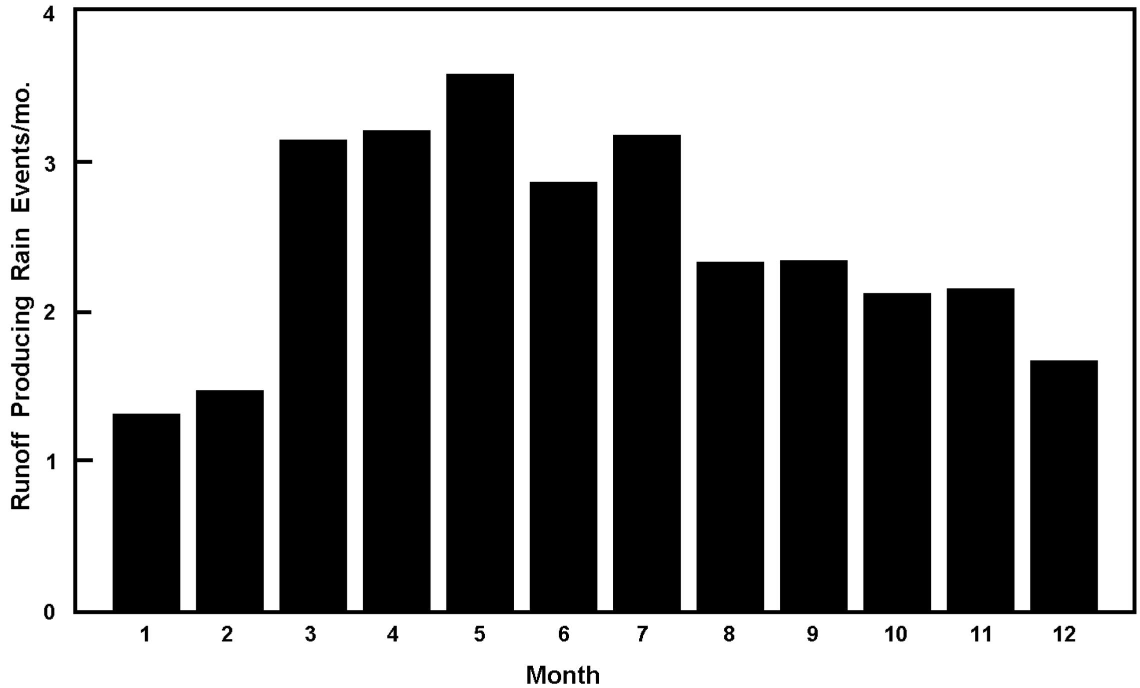

Figure 9-6. Runoff producing events per month in Boulder, CO.

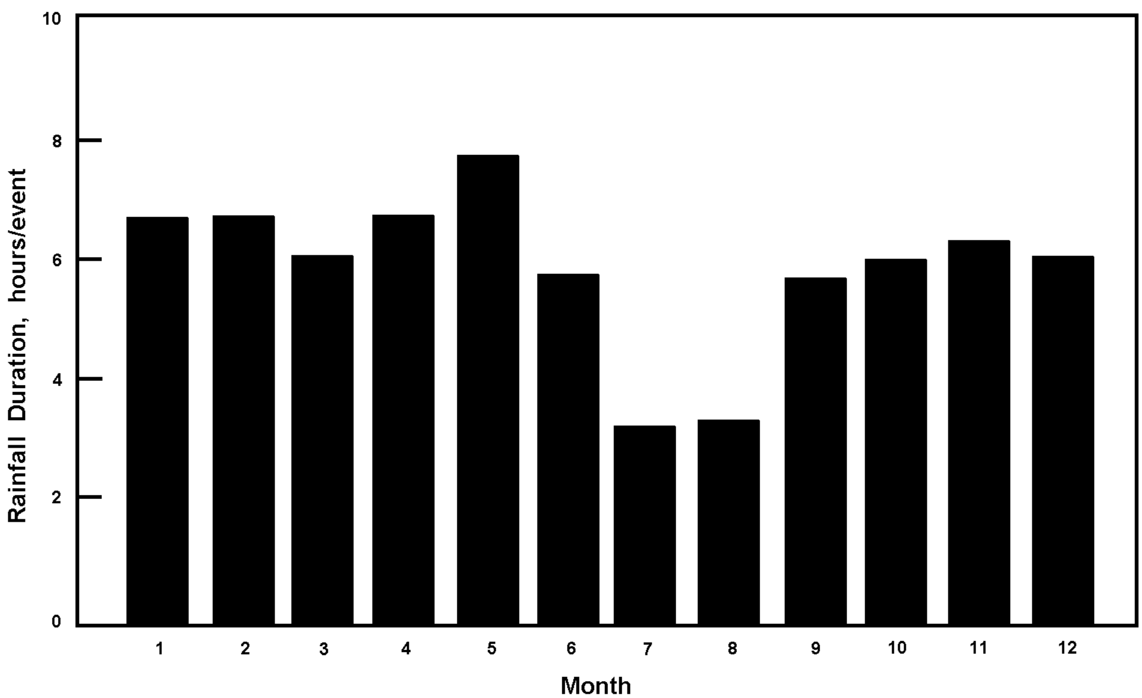

Figure 9-7. Average rainfall duration per event in Boulder, CO.

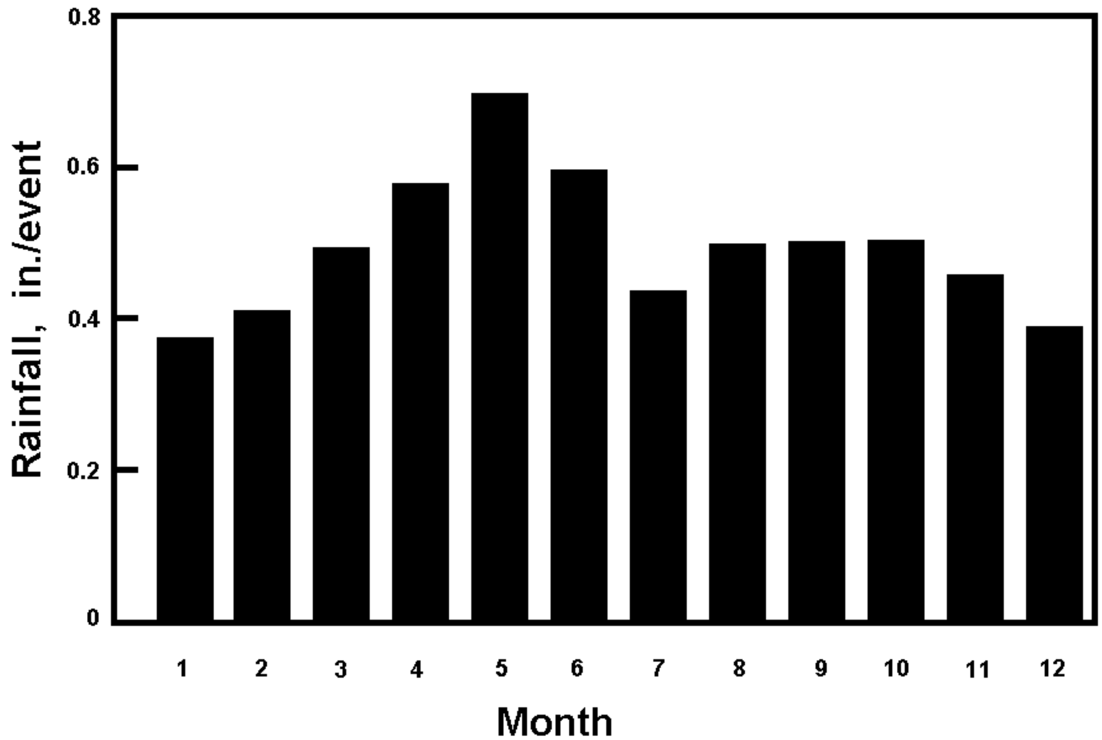

Figure 9-8. Average rainfall per event for Boulder, CO.

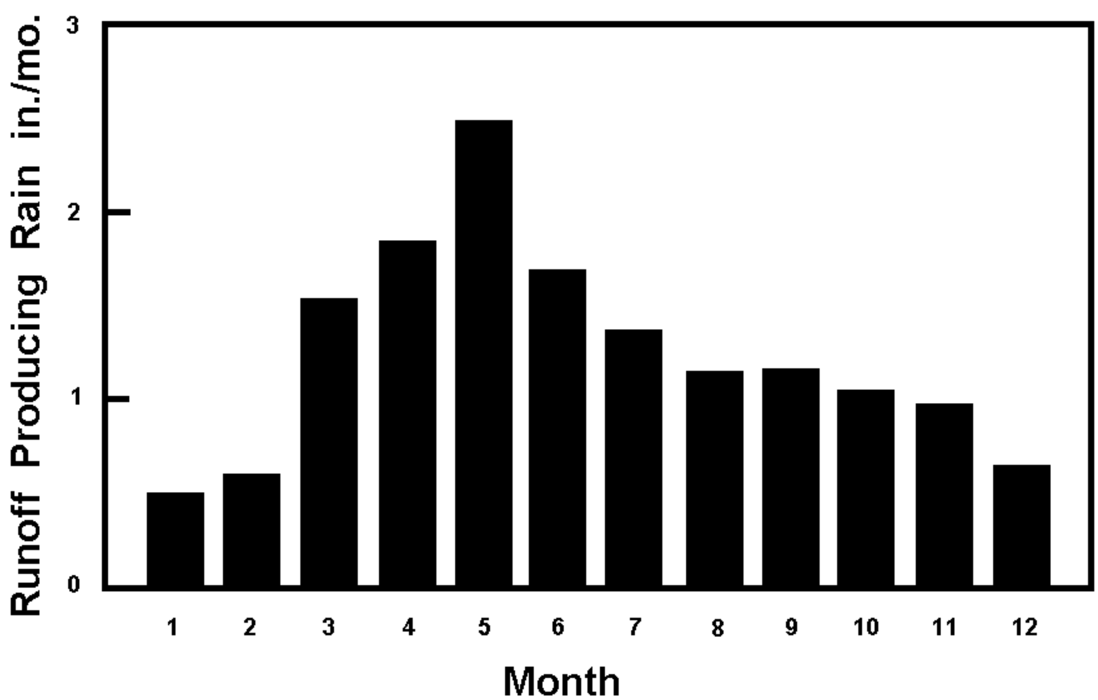

Figure 9-9. Average runoff producing rainfall per month for Boulder, CO.

Table 9-4. Summary of surface water records for Boulder Creek Watershed.

ID	Name	Drainage Area (mi^2)	Period of Record From	Period of Record To	Average Discharge (cfs)	Average Discharge (cfs/mi^2)	Average Discharge (inch/yr)	Upstream Diversion	Storage (ac-ft.)
6726000	N. Boulder C. @ Silver Lake	8.7	1913	1932					
6726500	N. Boulder C. nr. Nederland	30.4	1929	1931					
6725500	Boulder C. at Nederland	36.2	1907	Now	54.3	1.50	20.36	0	Small
6726900	Bummers Gulch nr. El Vado	3.87	1983	Now	0.5	0.13	1.75	0	0
6725500	Boulder C. nr. Orodell	102	1906	Now	86.6	0.85	11.52	Yes, Boulder	11500
6727500	Fourmile C. at Orodell	24.1	1947	1953	6.48	0.27	3.65	?	?
			1982	Now					
6729000	S. Boulder C. nr. Rollinsville	42.7	1910	1918					
			1945	1949					
6729300	S. Boulder C. at Pinecliff	72.7	1979	1980					
6725500	S. Boulder C. nr. Eldorado Spgs.	109	1980		76	0.70	9.46	Big Influence	
6730200	Boulder C. at N. 75th St.	304	1986	Now	90.9	0.30	4.06	Big Influence	Much
6730300	Coal R. nr. Plainview	15.1	1959		4.62	0.31	4.15	None	
6730500	Boulder C. @ Mouth nr. Longmont	439	1927	1949				Big Influence	Much
			1951	1955					
			1978	1990					

Source: Surface water records of the U.S. Geological Survey.
Flows strongly affected by numerous reservoirs and diversions.

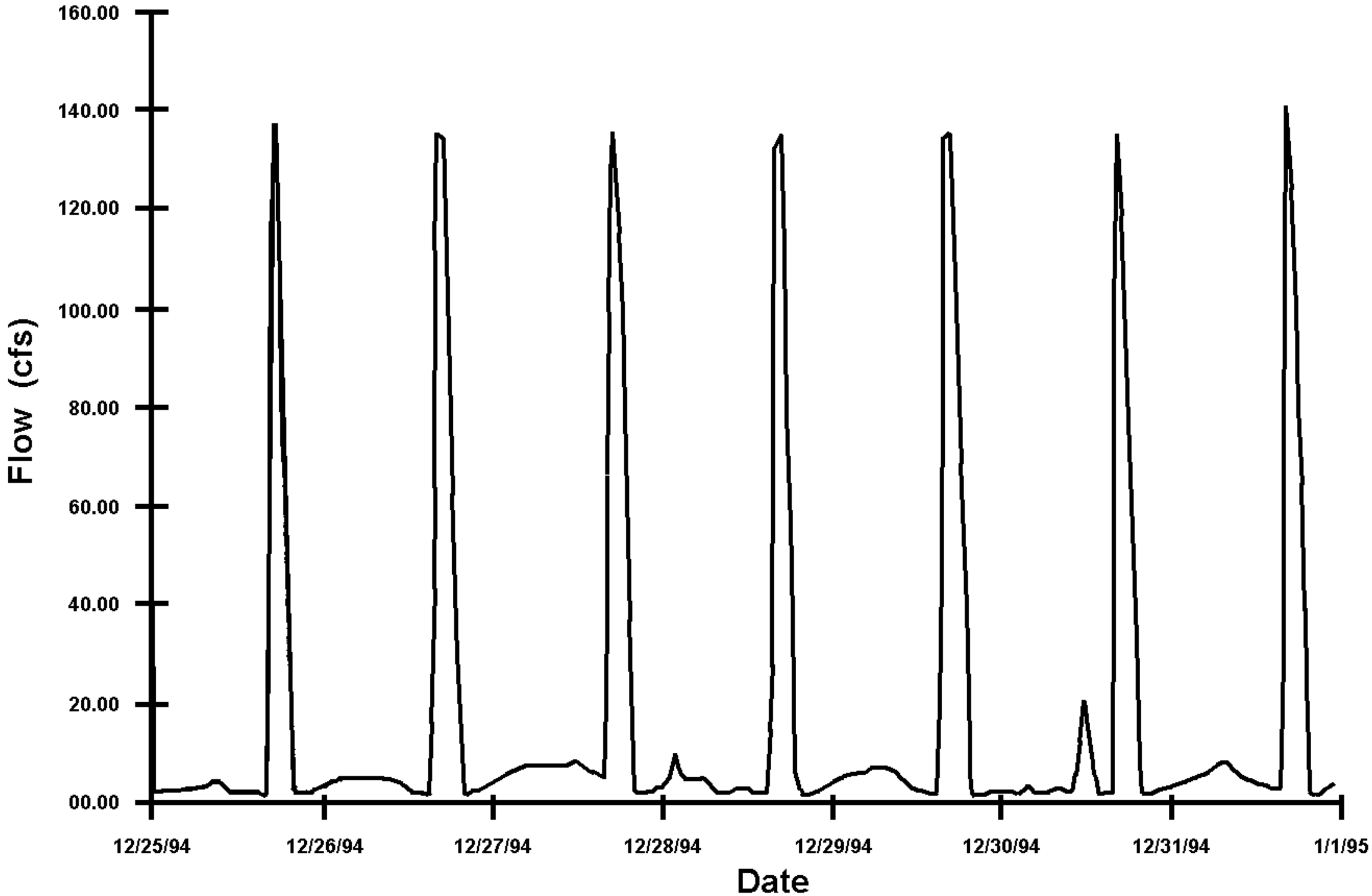

Figure 9-10. Boulder Creek streamflow at Orodell, CO.

The flows in the lower portion of Boulder Creek from 75th St. to its confluence with the St. Vrain River are affected by wastewater treatment plant effluent, Colorado-Big Thompson deliveries from the Boulder Creek Supply Canal, and numerous ditch diversions and return flows. Low flows above 75th St. occur in May and October due to filling of Baseline, Panama, Six-Mile, and Valmont reservoirs. Lowest flows in this section occur in late summer due to diversions for irrigation. Winter flows have increased due to increased releases by PSCO but with a wide range from 1 to 140 cfs over a daily cycle. This pulsed flow occurs only a few hours per day for peaking power.

Middle Boulder Creek has a long-term gage at Nederland just upstream from Barker Dam. This station provides the best estimate of what the unmodified alpine hydrology might look like. Boulder Creek at Orodell includes the contribution of North Boulder Creek. Streamflows at Orodell are affected by the upstream storage in Barker Dam and major diversions for urban water supply and hydropower. Fourmile Creek at Orodell flows can be added to the Boulder Creek at Orodell to get a good estimate of part of the inflow to the urban portion of Boulder Creek.

Within the City of Boulder, numerous diversions take place. Many of the early diversions were for irrigation. These diversions constitute a complex water network, which is difficult to understand as will be discussed in the diversions section.

The Boulder Creek at N. 75th St. gage includes the direct flows in Boulder Creek as the water moves through the City of Boulder. Other components are the sewage effluent from the City, which discharges a few hundred feet above the gage, and numerous other tributary inflows including part of the South Boulder Creek inflow, urban runoff, drainage from local stream channels, and canal inflows to satisfy downstream water rights.

The gage on Boulder Creek at the mouth near Longmont is a discontinued station. Fortunately, there is some overlap with the 75th St. station. Flows in this last section of the stream are heavily affected by agricultural and urban withdrawals and return flows. This section of Boulder Creek between 75th St. gage and Longmont typically loses flow.

South Boulder Creek

The natural runoff of South Boulder Creek at Eldorado Springs is estimated to be about 0.67 cfs/mi^2 (WBLA 1988). The only current station for South Boulder Creek is at Eldorado Springs where South Boulder Creek leaves the mountains. The flows at this station are strongly affected by upstream Gross Reservoir, which is owned by the City of Denver and diverts water from the basin. Downstream of Eldorado Springs, the flow in South Boulder Creek is subject to numerous diversions. These diversions leave South Boulder Creek without water during some months of the year. Because of the lack of stream gages, the quantity diverted and where it enters Boulder Creek is speculative.

Groundwater

To date, relatively little attention has been given to groundwater and the interrelationship between groundwater and surface water. This may change as competition for the available water continues to intensify. No active groundwater monitoring wells are maintained in the study area.

Land Use and Growth Management in Boulder Valley

General

A comprehensive plan has been developed for Boulder Valley (City of Boulder Planning Department and Boulder County Land Use Department 1990). This plan is updated frequently. For planning purposes, the Boulder Valley is divided into the Service Area which is the area serviced by the Boulder Utilities and the Planning Area which includes the Service Area and outlying areas, typically open space areas. The breakdown of land use for the Service Area is shown in Table 9-5 and Figure 9-11. The total service area is 17,225 acres. A roughly equal size of area constitutes the remainder of the total planning area yielding a total planning area of about 35,000 acres.

The City of Boulder has a long tradition of open space land acquisition as chronicled in Figure 9-12 (City of Boulder 1995). In response to rapid population growth during the 1950's and 1960's, Boulder established a "blue line" above which City water would not be provided. The intended effect was to slow the rate of development in the foothills. In 1967, Boulder became the first city in the United States to tax themselves for the acquisition, management, and maintenance of open space land. The increase in the sales tax was 0.4%. In 1989, an additional 0.33% sales tax was approved by the voters for the same purpose. As of 1993, 20,000 acres of land have been protected at a cost of $67 million. By 1995, the total amount of open space land has reached 25,000 acres. The current holdings of the open space program are shown in Figure 9-13.

An ecosystems approach has been used in prioritizing these land acquisitions. With regard to water resources, this has resulted in acquisition of additional water rights which can be used for instream flow needs, reduction in nonpoint loads from lands that would otherwise have been developed, stream restoration, and acquisition of floodplains and wetlands. Recreational use of these open space lands is very high. The 1993 annual level of activity was about 1.7 million visits to this open space land. These recreational uses include hiking, jogging, pet exercising, bicycling, wildlife viewing, horseback riding, and fishing.

In addition to open space acquisition by the City of Boulder, Boulder County has had an aggressive open space acquisition program. This program is supported by sales tax revenues, which currently yield about $4 million per year for open space acquisition. To date, Boulder County has acquired about 35,000 acres of land. Finally, a significant part of the mountain portion of the Boulder Creek Watershed is owned by the U.S. Forest Service. Thus, a very high percentage of the upper watershed land is in public ownership. This provides an excellent opportunity for linked water and land management.

In addition to the open space program, Boulder has an aggressive growth management program. Before growth management, the expected built-out for the water supply system was a population of 250,000. Growth management decisions have reduced this number by 36% to 160,000 (WBLA 1988). This major reduction in growth, coupled with a major open space acquisition program, has greatly reduced the potential impact of urbanization on the water infrastructure system. In the long-run, this is probably the most effective water management tool.

Relative Importance of Urban Land Use

The planning area for Boulder County was divided into 40 drainage basins as shown in Table 9-6. The total drainage area upstream of Boulder is over 84,000 acres (Reaches 1 and 2). Virtually all of this land is undeveloped. Much of it is in public ownership including large U.S. Forest Service holdings. The only current upstream activity is small urban areas, the largest of which is Nederland, a small town located about 20 miles upstream.

The daily runoff was estimated for each of the basins within the City. The western part of the City is grouped into Urban Runoff 1, which consists of eight small drainage areas (Reaches 3-10), the largest of which is 68 acres. Then, Gregory Creek enters Boulder Creek. It drains predominantly undeveloped land, much of it in the protected open space program. The next area draining Boulder Creek is called Urban Runoff 2. It comprises Reaches 12-26 and has a drainage area of 738 acres. Then, Bear Creek enters Boulder Creek. Most of the drainage in Bear Creek is in the open space area. Next, Reaches 28-31 enter Boulder Creek between Bear Creek and Goose Creek. About two thirds of Goose Creek is urban. The last urban runoff group, Urban Runoff 4, enters Boulder Creek between Goose Creek and Wonderland Creek. Then, Wonderland Creek and Fourmile Creek enter Boulder Creek. Lastly, some nonurban lands drain to Boulder Creek between Fourmile Creek and the Wastewater Treatment Plant.

Table 9-5. Land use in the City of Boulder, CO service area – 1995 (City of Boulder Planning GIS Laboratory, unpublished information).

	Area (acres)						
Subcommunity	Residential	Business	Industrial	Open Space	Parks	Public	Total
Central Boulder	2,010	104	0	88	175	154	2,531
North Boulder	1,268	97	63	588	131	55	2,202
U. of Colorado	85	8	0	16	17	508	634
Palo Park	396	23	0	120	10	63	612
Crossroads	252	375	69	30	34	11	771
South Boulder	1,649	33	176	1,280	208	110	3,456
East Boulder	147	5	1,242	207	5	196	1,802
Southeast Boulder	1,862	92	43	218	223	186	2,624
Gunbarrel	1,113	36	1,074	315	36	19	2,593
Total	8,782	773	2,667	2,862	839	1,302	17,225
% of Total	51.0	4.5	15.5	16.6	4.9	7.6	100.0

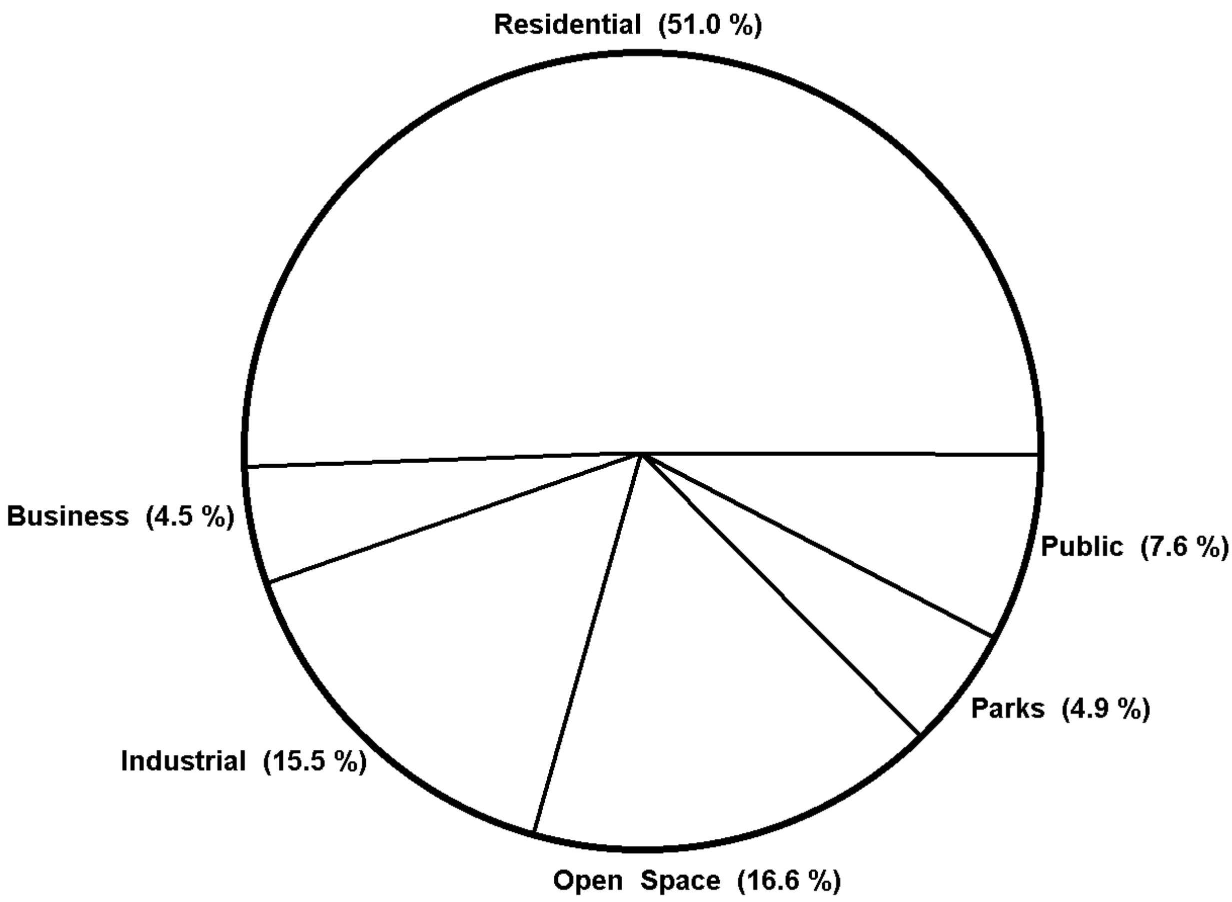

Figure 9-11. Land use in the City of Boulder, CO service area, 1995 (City of Boulder planning GIS laboratory, unpublished information).

1898	Purchase of Chautauqua Park at the foot of Flagstaff Mountain through a bond issue, the beginning of the Boulder Mountain Parks System.
1907	Receipt of 1,600 acres on Flagstaff Mountain from a Congressional grant for the Mountain Parks System.
1910	Frederick L. Olmstead suggests a program for preserving scenic Open Space lands.
1916	Purchase of 1,200 additional acres on Green Mountain and Bear Peak for the Mountain Parks System.
1950-1960	Boulder's population nearly doubles from 19,999 to 37,718.
1959	Concerned citizens organize to form a group now known as PLAN-Boulder County.
1959	An amendment to the City Charter establishes a "blue line" above which City water will not be supplied. Citizens who helped pass the amendment realized that this would slow development of the foothills, but not stop it.
1960-1970	Boulder's population again nearly doubles from 37,718 to 68,870.
1963	PLAN Boulder County successfully campaigns for a bond issue to save the 160-acre Enchanted Mesa from development. It is added to the Mountain Parks System.
1965	Citizens defeat a ballot proposal to extend services to a proposed development south of Boulder.
1967	Boulder citizens vote to become the first city in the nation to tax themselves for the acquisition, management, and maintenance of open space land. The measure to permanently increase sales tax by four-tenths of one percent, or $0.004, passes with 61% of the vote.
1971	An amendment to the City Charter authorizes the City to incur debt to acquire Open Space, allowing for an expanded land acquisition program.
1973	City Council creates the Open Space Board of Trustees to set policies and priorities for acquisition and management of Open Space land.
1978	Boulder Valley Comprehensive Plan (BVCP) states that Open Space shall provide "an important framework for land use planning in the Boulder Valley."
1986	An amendment to the City Charter provides more permanent protection for Open Space lands, and establishes the Open Space Board of Trustees and the Open Space Department in the Charter, with support of 79% of the voters.
1989	Funding for the accelerated acquisition program passes with 76% of the vote. This adds an additional 0.33 percent sales tax ($0.0033) for the 15-year period from 1990 through 2004.
1993	Authority to spend all Open Space sales tax revenues and continue to enter into debt for

Figure 9-12. Boulder open space chronology of events (City of Boulder, 1995).

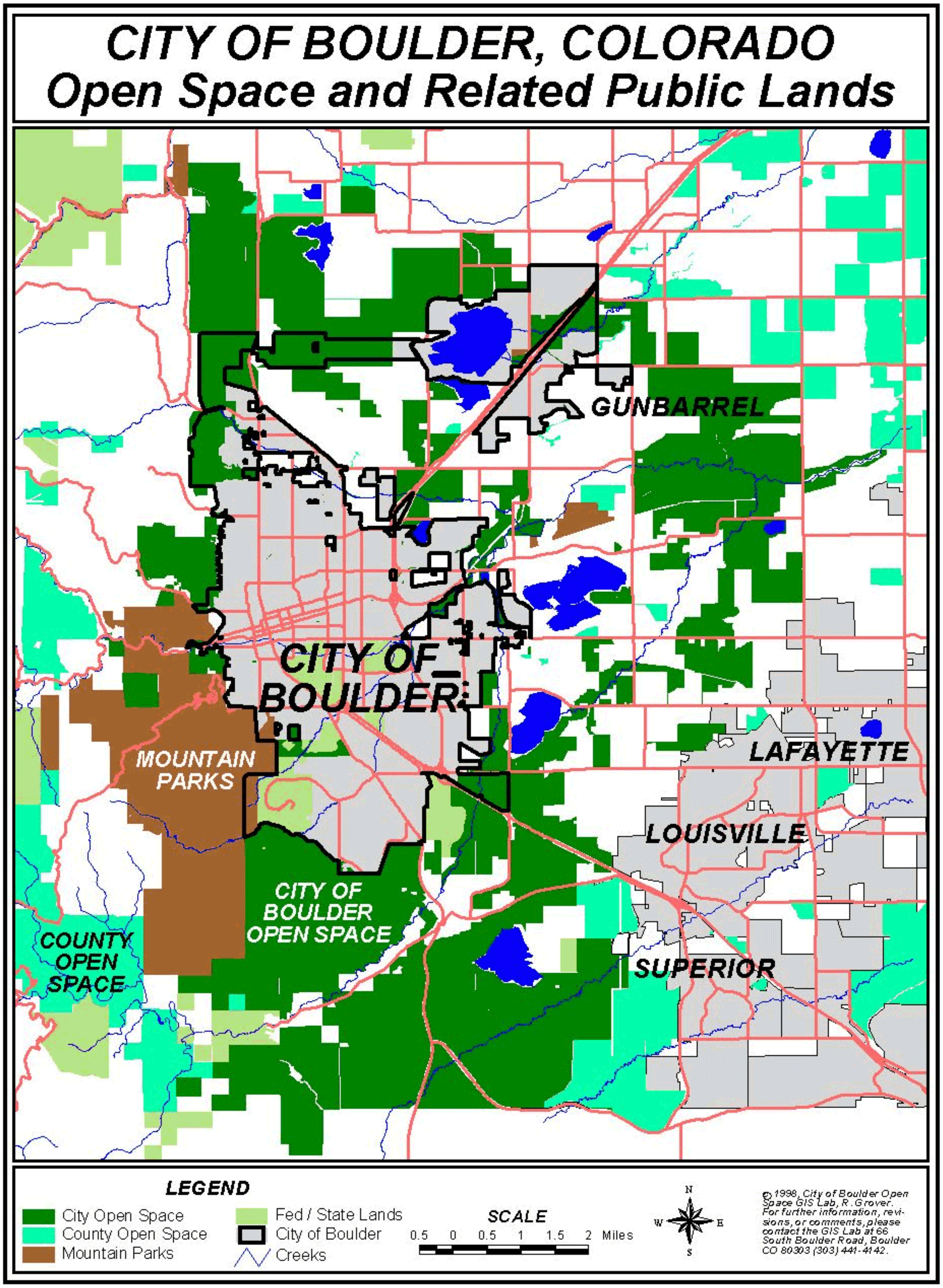

Figure 9-13. Boulder open space and public lands (City of Boulder, 1998).

Table 9-6. Drainage areas for Boulder and Boulder Creek Watershed.

Individual Catchments

Reach	Feet Upstream	Individual Name	Group Name	Area (acres) Total	Urban	Undev.	Imperviousness (decimal) Average	Urban	Undev.
1	134,200	Boulder C.	Boulder C.	83,200.0	0.0	83,200.0	0.04	0.5	0.04
2	134,100	Sunshine Canyon C.	Sunshine Canyon C.	1,165.0	0.0	1,165.0	0.04	0.5	0.04
3	131,050	DFA 1	Urban Runoff 1	24.9	24.9	0.0	0.50	0.5	0.04
4	130,075	DFA 2	Urban Runoff 1	22.5	22.5	0.0	0.50	0.5	0.04
5	130,020	DFA 19	Urban Runoff 1	9.6	9.6	0.0	0.50	0.5	0.04
6	129,030	DFA 3	Urban Runoff 1	67.2	67.2	0.0	0.50	0.5	0.04
7	129,003	AFA C-5	Urban Runoff 1	67.7	67.7	0.0	0.50	0.5	0.04
8	128,025	AFA C-2	Urban Runoff 1	50.9	50.9	0.0	0.50	0.5	0.04
9	127,095	AFA C-6	Urban Runoff 1	22.3	22.3	0.0	0.50	0.5	0.04
10	127,090	AFA D-1	Urban Runoff 1	66.3	66.3	0.0	0.50	0.5	0.04
11	127,085	Gregory C.	Gregory C.	1,465.6	315.4	1,150.2	0.139	0.5	0.04
12	127,080	AFA C-8	Urban Runoff 2	20.0	20.0	0.0	0.50	0.5	0.04
13	125,010	DFA 4	Urban Runoff 2	35.6	35.6	0.0	0.50	0.5	0.04
14	125,000	C-7	Urban Runoff 2	48.5	48.5	0.0	0.50	0.5	0.04
15	124,015	DFA 5	Urban Runoff 2	42.6	42.6	0.0	0.50	0.5	0.04
16	123,005	D-2	Urban Runoff 2	176.2	176.2	0.0	0.50	0.5	0.04
17	123,000	DFA 6	Urban Runoff 2	41.9	41.9	0.0	0.50	0.5	0.04
18	121,060	D-3	Urban Runoff 2	48.7	48.7	0.0	0.50	0.5	0.04
19	121,058	DFA 7	Urban Runoff 2	19.8	19.8	0.0	0.50	0.5	0.04
20	121,057	C-9	Urban Runoff 2	15.9	15.9	0.0	0.50	0.5	0.04
21	120,004	DFA 8	Urban Runoff 2	23.8	23.8	0.0	0.50	0.5	0.04
22	120,003	C-10	Urban Runoff 2	8.1	8.1	0.0	0.50	0.5	0.04
23	117,025	DFA 9	Urban Runoff 2	45.7	45.7	0.0	0.50	0.5	0.04
24	115,060	C-3	Urban Runoff 2	30.7	30.7	0.0	0.50	0.5	0.04
25	115,045	C-4	Urban Runoff 2	91.2	91.2	0.0	0.50	0.5	0.04
26	115,030	DFA 10	Urban Runoff 2	89.2	89.2	0.0	0.50	0.5	0.04
27	114,000	Bear Creek	Bear Creek	5,273.6	1,456.0	3,817.6	0.167	0.5	0.04
28	113,080	E-1	Urban Runoff 3	99.1	56.0	43.1	0.30	0.3	0.04
29	113,075	DFA 11	Urban Runoff 3	46.1	26.1	20.0	0.30	0.3	0.04
30	113,070	E-2	Urban Runoff 3	166.3	94.0	72.3	0.30	0.3	0.04
31	109,065	DFA 15	Urban Runoff 3	52.9	29.9	23.0	0.30	0.3	0.04
32	108,100	Goose Creek	Goose Creek	3,494.4	2,294.1	1,200.3	0.342	0.5	0.04
33	108,006	DFA 13	Urban Runoff 4	23.8	18.6	5.2	0.40	0.4	0.04
34	108,005	DFA 14	Urban Runoff 4	193.8	151.7	42.1	0.40	0.4	0.04
35	108,000	B	Urban Runoff 4	255.3	199.8	55.5	0.40	0.4	0.04
36	107,099	A	Urban Runoff 4	237.5	185.9	51.6	0.40	0.4	0.04
37	107,095	DFA 18	Urban Runoff 4	18.2	14.2	4.0	0.40	0.4	0.04
38	106,050	Wonderland C.	Wonderland C.	1,222.4	430.5	791.9	0.202	0.5	0.04
39	100,000	Fourmile Canyon C.	Fourmile Canyon C.	6,419.2	781.5	5,637.7	0.096	0.5	0.04
40	91,000	WW Treat. Plt.	WW Treat. Plt.	500.0	65.2	434.8	0.10	0.5	0.04
		Total area above Boulder		84,365.0	0.0	84,365.0			
		Total area in Boulder		20,537.5	7,188.2	13,349.3			
		Total area below Boulder		104,902.5	7,188.2	97,714.3			

Aggregated Areas

Number	Station	Group Name	Acres
1	134,200	Boulder C.	83,200.0
2	134,100	Sunshine Canyon C.	1,165.0
3	128,924	Urban Runoff 1	331.4
4	127,085	Gregory C.	1,465.6
5	120,830	Urban Runoff 2	737.9
6	114,000	Bear Creek	5,273.6
7	112,073	Urban Runoff 3	364.4
8	108,100	Goose Creek	3,494.4
9	107,641	Urban Runoff 4	728.6
10	106,050	Wonderland C.	1,222.4
11	100,000	Fourmile Canyon C.	6,419.2
12	91,000	Wastewater Treatment Plant	500.0
		Total Area	104,902.5

Because of the open space land acquisition program, the public ownership of the upstream drainage area, and the growth management program, Boulder has been able to minimize the amount of urban runoff generation by minimizing urban land use. Only 7,200 acres out of a total of 20,500 acres in the local drainage generate urban runoff. With upstream drainage of over 84,000 acres, only about seven percent of the land use in the Boulder Creek Watershed above 75th St. is urban. Thus, urban runoff would be expected to be a relatively small portion of the total runoff based on land use analysis.

Water Management Infrastructure

Storage

Natural storage in BCW consisted of a few alpine lakes. However, because of the highly variable nature of the streamflow, construction of storage reservoirs was essential. Barker Dam on Middle Boulder Creek was built in 1910. Seven storage reservoirs were built in North Boulder Creek about the same time. Gross Reservoir on South Boulder Creek was built by the City of Denver to store and divert water for its purposes. Within the plains portion of BCW, numerous reservoirs have been built throughout the basin in order to store water including Boulder Reservoir, Valmont Reservoir, and Baseline Reservoir. Boulder Reservoir was built in 1954 at a cost of $1,190,800 as part of Boulder's contribution for participating in the Colorado-Big Thompson Project, which brings water from the north into Boulder Reservoir. Its original capacity was 12,700 acre feet. Overall, there are about 25 to 30 reservoirs in the valley, each one operated to accomplish local or specific objectives within the overall water resources system.

Canals

An extensive canal network has been constructed during the past 140 years. Early canals were built from the mountains to the valleys to maximize gravity flow. Coupled with the storage reservoirs, these canals form a complex water delivery system. Many of the "canals" were parts of the minor tributary system. Thus, the distinction between a "receiving water" and a "canal" is a blurred one at best since these open canals also serve as drainage ditches. This has implications for water quality management.

Control Works

A total of 27 major control works exist in the BCW. Two diversion structures are on North Boulder Creek. These control structures control reservoir releases to the Lakewood pipeline. The main control structure in the upper portion of Middle Boulder Creek is at Barker Dam. This structure directs water into the pipeline, which is shared by the City of Boulder and PSCO. In the valley portion of BCW, diversion structures exist at the mouth of the canyon, at Broadway, and along the downstream portions of the main stem of Boulder Creek. South Boulder Creek has 12 diversion structures on its banks. Each of these diversion structures feeds water into a canal and/or reservoir system which may further branch out to additional canals and associated control structures.

Pipelines

Two major pipelines in the system are located in North Boulder Creek. Lakewood Pipeline was originally installed to protect the City's water supply from contamination by mining activities in the early 1900's. The other pipeline goes from Barker Dam on Middle Boulder Creek to the PSCO generating facilities and the City's Betasso Water Treatment Plant. This 50 cfs pipeline was originally constructed by PSCO which now shares it with the City of Boulder. These two diversions have a major impact on streamflows in the mountain portion of BCW.

Imports and Exports

The major importation of water occurs from the north as part of the Colorado-Big Thompson and Windy Gap Projects. This water enters the Boulder Creek Watershed via an open canal that discharges into Boulder Reservoir north of Boulder. The major export is from Gross Reservoir on South Boulder Creek to the City of Denver. Also, numerous diversions from Boulder Creek occur as the stream enters the city.

Current Water Management System

The current water management system bears little resemblance to the natural system. Reservoirs, canals, diversion structures, and a complex prior appropriation water doctrine have evolved to dictate the operation of the contemporary system.

Water Quantity

Area inhabitants have used BCW for virtually all purposes. Also, BCW has impacted inhabitants through flooding and other undesirable factors. A summary of these activities is presented below.

Municipal Water Supply and Wastewater Return

The City of Boulder began operating a water supply system in 1874. However, even at that early date, much of the water had been preempted for agricultural and mining purposes. Thus, the City's junior water right left them vulnerable during low flow periods. In response, Boulder began to acquire some agricultural water rights and constructed more storage capacity. In response to pollution from upstream mining activities, the City relocated its intake upstream on two occasions. Finally, Boulder placed the intake in the headwaters of the BCW and the water was transported to the City via the Lakewood pipeline, which was completed in 1906. They also acquired the entire headwaters of the watershed to protect the water from pollution.

This system functioned well until the serious drought of the early 1950's forced the City of Boulder to further supplement their system with a water rights exchange agreement, which allowed the City to use more upper basin water in exchange for providing an equivalent amount of water downstream. Also, Boulder acquired significant storage rights in Barker Reservoir from PSCO and the ability to transport this water to their treatment plant via a pipeline. Finally, Boulder joined the Colorado-Big Thompson Project to obtain water from the north. The City built Boulder Reservoir north of Boulder as part of this agreement.

These acquisitions provided Boulder with a major improvement in the reliability of their system. Relatively recent master plans for the water supply system have been prepared by WBLA (1988) and Brown and Caldwell (1990).

The water demand for Boulder for 1992 was 19.73 mgd with peak monthly demand of 32.45 mgd in July as shown in Table 9-7. About 62% of the demand is for indoor use and the remainder is for outdoor use. However, most of the summer water demand is for outdoor use as shown in Table 9-7 and Figure 9-14.

Much of the urban water use is returned to Boulder Creek at 75th St. after treatment. For 1992, the average return flow from the treatment plant was 17.41 mgd. About 5.1 mgd of this total is estimated to be infiltration as shown in Table 9-7 and Figure 9-15. Lastly, the WWTP flow and the streamflow are compared in Table 9-7 and Figure 9-16. The WWTP effluent flow is larger than the streamflow in the colder months of the year.

Agricultural Water Supply

Irrigation using Boulder Creek water is practiced in the valley portion of BCW. Major diversions for agricultural water use occur at eight locations along Boulder Creek as it moves through the City. For 1992, the average diversion for agriculture was 36.64 cfs. These diversions have a major impact on the amount of flow in Boulder Creek because they occur at the western end of the City.

Flood Control

Boulder has been plagued by flooding since its founding because the early settlers located close to Boulder Creek to have easy access for water supply. Smith (1987) has chronicled the evolution of Boulder's flooding problems since its inception. The first recorded flood was in 1864. Subsequent floods in 1867, 1876, and 1885 caused the creek to spread a mile and a half wide. The major flood of record occurred in 1894 with an estimated discharge of 7,400 cfs. This flood did major damage to the town. Continued problems with flooding prompted the City to hire consultants to make recommendations on how best to manage the problem. Mr. Frederick Law Olmstead, Jr. proved to be the most prophetic. In 1910, he recommended a plan, which is very similar to what the City adopted in 1985, 75 years later, that is, a linear park.

Flooding during the second decade of the 20th century broke the City's water line twice. The City remained indecisive for many years in spite of a constant stream of consulting studies, which recommended a wide variety of structural and non-structural solutions. As the City procrastinated, the problem became potentially worse. Nevertheless, progress was eventually made and Boulder has developed a sophisticated stormwater quantity and quality management program.

Table 9-7. Comparison of water use and wastewater flows, 1992.

Month	FLOW IN MGD							
	Water Demand			Wastewater Treatment Plant			Boulder Creek	
	Indoor	Outdoor	Total	Base	Infilt.	Total	Above WWTP	@ 75th St.
Jan	11.74	0.00	11.74	12.31	2.22	14.53	11.80	26.33
Feb	12.31	0.72	13.03	12.31	2.37	14.69	7.40	22.08
Mar	12.31	0.46	12.77	12.31	6.94	19.25	28.01	47.26
Apr	12.31	5.46	17.77	12.31	5.99	18.31	35.72	54.03
May	12.31	13.99	26.30	12.31	5.50	17.81	69.83	87.64
Jun	12.31	13.52	25.83	12.31	6.28	18.59	65.56	84.14
Jul	12.31	20.14	32.45	12.31	6.51	18.82	105.22	124.04
Aug	12.31	13.59	25.90	12.31	7.03	19.34	68.99	88.33
Sep	12.31	15.09	27.40	12.31	6.40	18.71	13.91	32.62
Oct	12.31	6.43	18.74	12.31	4.81	17.12	9.46	26.58
Nov	12.31	0.19	12.50	12.31	3.75	16.06	8.30	24.36
Dec	12.31	0.00	12.31	12.31	3.39	15.70	15.66	31.35
Avg.	12.26	7.47	19.73	12.31	5.10	17.41	36.65	54.07
% of Total	62.2	37.8	100.0	70.7	29.3	100.0		

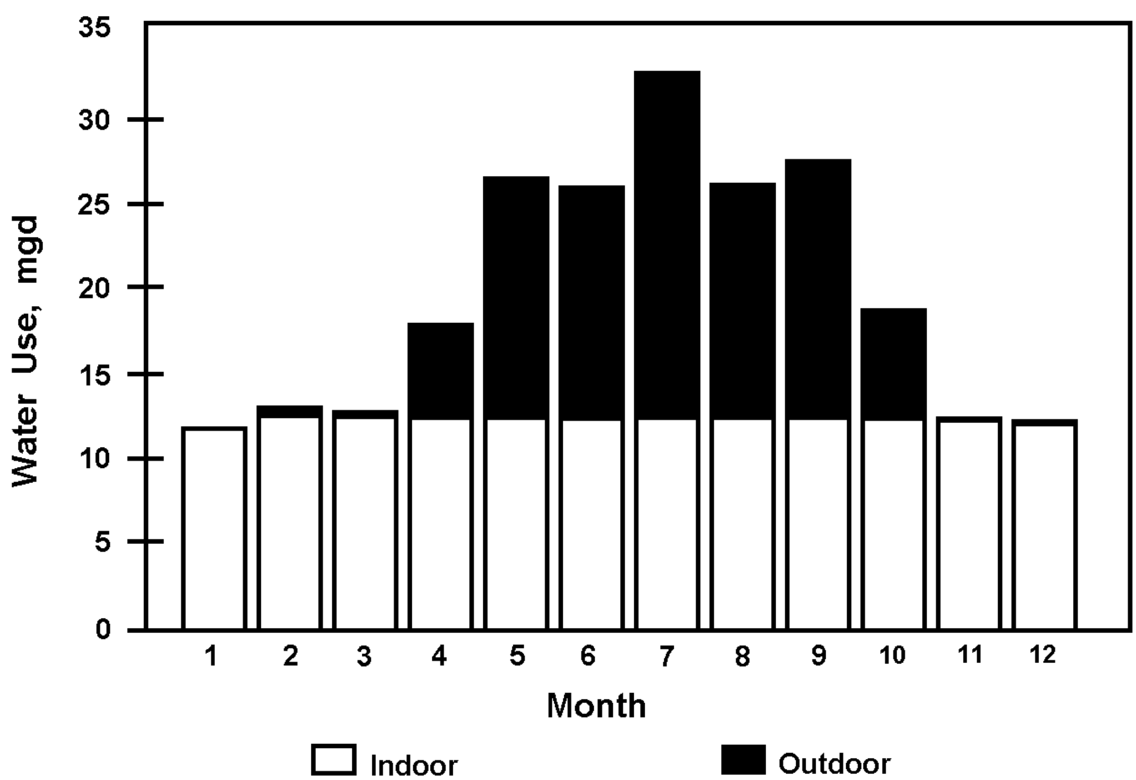

Figure 9-14. Monthly water use for Boulder, CO, 1992.

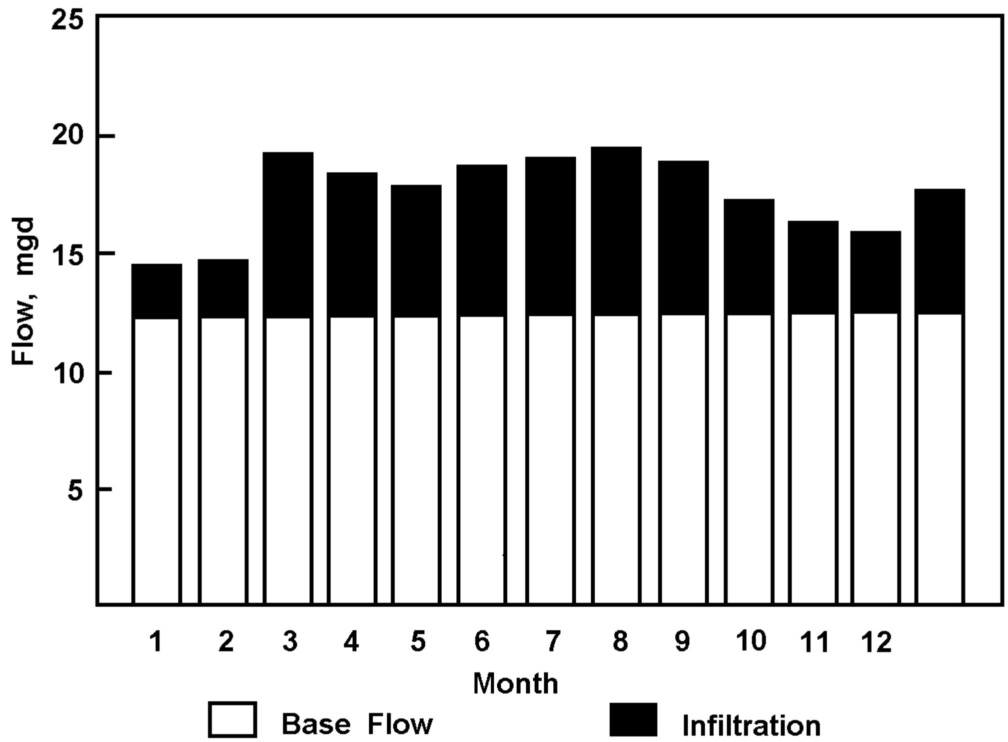

Figure 9-15. Monthly wastewater volumes for Boulder, CO, 1992.

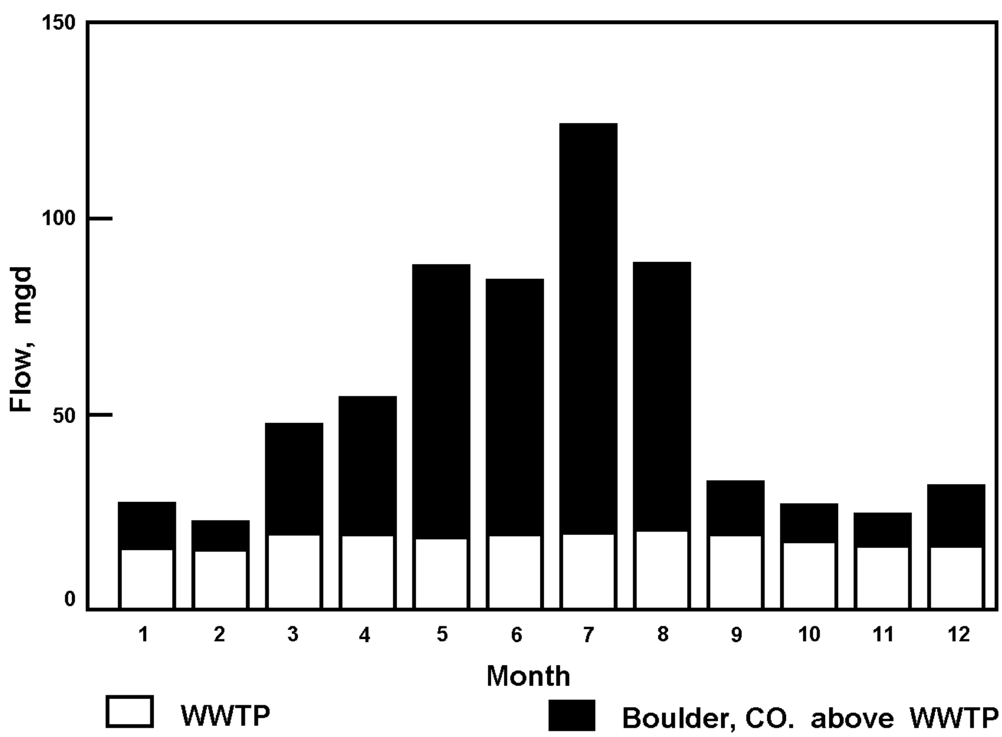

Figure 9-16. Monthly wastewater and Boulder Creek flows, 1992.

However, Boulder remains the most at risk community in Colorado for potential flooding due to its development in relatively high hazard areas and the flashy nature of floods in this area. Boulder has taken a benefit-cost-risk approach to stormwater management. Using a combination of nonstructural and structural controls, they have delineated facilities which can be built and remain in the floodplain. Typically, these buildings are public buildings such as government offices and the library. A floodplain map, shown in Figure 9-17, indicates that much valuable property in downtown Boulder and parts of University housing remain at risk.

Greenway Program

With increased diversions over time, Boulder Creek was literally dried up by mid to late summer. In the 1960's and 1970's, the community began to be concerned about rapid growth. An outcome of that concern was a desire to maintain urban stream corridors as community amenities. Described in this section is the manner in which this desire was articulated in the 1978 Boulder Valley Comprehensive Plan.

An underlying principle was that the functional and aesthetic qualities of drainage courses and waterways shall be preserved and enhanced in a manner compatible with a basically non-structural approach to flood control. In particular, a non-containment approach to flood management was to be followed for Boulder Creek.

Beginning in the 1970's, a succession of plans proposed a trail along the creek. The final design, which emerged in the mid 1980's, called for restoring environmental features and establishing a non-motorized corridor along the creek. A series of objectives were identified including:

1. Create an offstreet non-motorized transportation system.
2. Preserve and enhance fish and wildlife habitat.
3. Protect ecologically sensitive areas.
4. Expand recreational use.
5. Protect water rights of multiple irrigation companies.
6. Maintain and improve flood carrying capacity of the waterway.
7. Protect water quality.
8. Provide opportunities for active and passive recreation.

The final design included strategies to revitalize the creek for fish, wildlife and recreation, including engineering whitewater boating features, enhancing fisheries habitat, and developing paved and gravel pathways to serve bicyclists, walkers, joggers and the disabled. A total of 65 fish habitat improvements were included. Structures included upstream v-dams, angled boulder dams, boulder deflectors, s-dams, and double wing deflectors. Ripple and pool areas provide desirable fish habitat especially during rapid changes in flow due to hydropower generation.

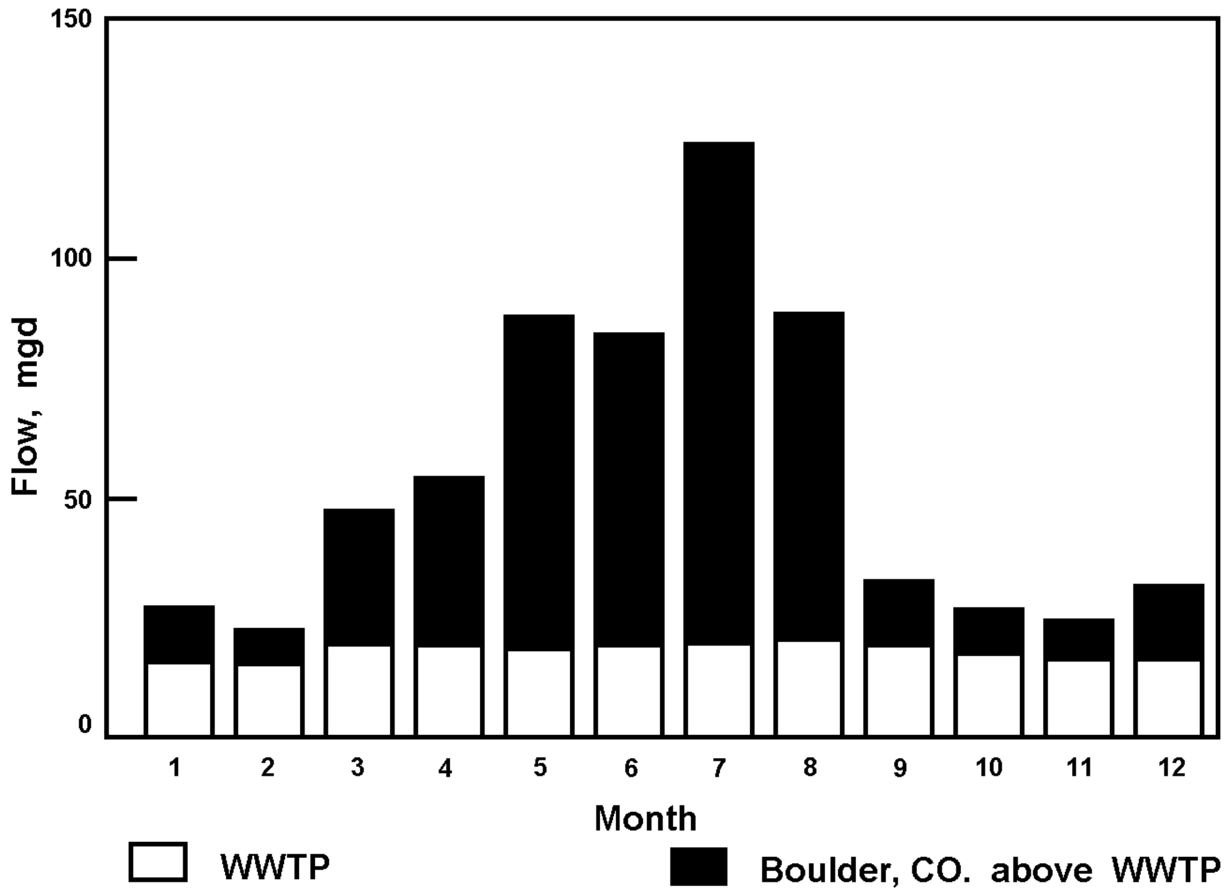

Figure 9-17. Boulder Creek potential flood inundation.

BCW has a very high recreational value to the community, especially after its restoration during the 1980's. A linear park with a bike path were constructed and much instream restoration work was done to help return the stream to a more natural appearance. This work has won a national award for innovative design. Also, Boulder's greenway is one of eight nationally to be featured in a recent book on greenways (Smith and Hellmund, eds. 1993). The Boulder Creek linear park system is heavily used for activities such as walking, jogging, biking and roller blading. Fishing, kayaking and tubing are popular in the upper reaches of Boulder Creek within the City. Boulder Creek was used as the kayak course for the 1995 Olympic Festival.

The original five-mile long Boulder Creek Greenway Project cost $3.3 million with about $1.3 million coming from State Lottery funds. The program continues to grow to include the rest of the Boulder Creek stream system. The current budget is over one million dollars per year. The idea of greenways has spread to other areas. Mayor Webb of Denver has made development of a greenway along the South Platte River as it moves through Denver a cornerstone of his current term in office. The 10 mile long restoration is expected to cost about $50 million and take ten years to complete.

With regard to the required flows for recreational uses, Boulder Creek, from the mouth of the canyon to 55th St., can support the recreational activities listed in Table 9-8.

Table 9-8. Recreational activities supported by flows in Boulder Creek.

Activity	Flow Range (cfs)	Months
Swimming	(1)	(1)
Wading	10-100	June-September
Kayaking	150-300	June-July
Tubing	50-100	July-August
Fishing	15-100	May-September
Fisheries Maintenance	> 15 cfs	May-September
	> 5 cfs	October-April

1) Swimming is not supported because velocities are too high and temperature and depth are too low.

Water quality has not been a major issue. The quality of the water is excellent. Urban runoff quality has not been a major concern. Primary episodes to date deal with spills and deliberate discharges of hazardous materials, such as paint, into the storm drains. In contrast, maintaining minimum instream flows has been a high priority concern. Prior to a major instream restoration effort in the mid 1980's, base flow in Boulder Creek as it moved through Boulder was often zero. Thus, an obvious part of stream restoration was to have adequate base flows, especially in late summer.

Hydropower

Hydropower is an important component of the BCW water resource system. PSCO provides most of the energy for the Boulder Valley and owns and operates Barker Dam on Middle Boulder Creek. Water is released from Barker Dam to a pipeline, which is used to transport the water to the generating facilities. The water is returned to Middle Boulder Creek just upstream from the Orodell gage. PSCO also diverts water from South Boulder Creek and Boulder Creek at 28th St. to Valmont Reservoir which is used for cooling water for its electric generating facilities in Boulder. PSCO has agreements with the City of Boulder for joint utilization of the storage in Barker Dam and for the pipeline to the generating facilities.

Hydropower releases can cause major variability in flows in Boulder Creek. During the winter months, flows are released only part of the day to meet early evening peaking requirements. These flows are pulsed to permit efficient use of the turbines. The hourly flows for Middle Boulder Creek at Orodell for late December 1994 are shown in Figure 9-10. The daily flows range from near 0 cfs for most of the day to about 140 cfs for the early evening hours. The flows for December 25, 1994 are shown in Figure 9-18. From midnight to about 5 pm, the flow in Boulder Creek is a few cfs. From 5 pm to 9 pm, the flow increases rapidly to about 136 cfs and then decreases rapidly back to 0 at about 9 pm. This highly variable flow would be expected to have a significant impact on the fisheries (WBLA 1988). Another concern is the diversion of Boulder Creek water at 28th St. to replenish Valmont Reservoir during the non-irrigation season. This diversion reduces low flows in the stream during fall and spring. Early fall, in particular, is a sensitive period for the receiving water.

Instream Flow Needs

As development in BCW proceeded, more of the available water resource was appropriated for the beneficial uses described above. These other uses left significant sections of BCW with little or no water during parts of the year. The cumulative impact of these diversions is that major problems occur with respect to fish and macroinvertebrate survival in all but the peak flow months from May through July as follows (Rozaklis 1994):

1. North Boulder Creek: Zero flow past Lakewood from October-March.

2. Middle Boulder Creek: Zero flow below Barker Dam from October-April.

3. Main Boulder Creek: Inadequate flow through the City. Periods of low or zero flow in late summer.

4. South Boulder Creek: Zero flow below Eldorado from November-March. Also, zero flows during latter part of the summer.

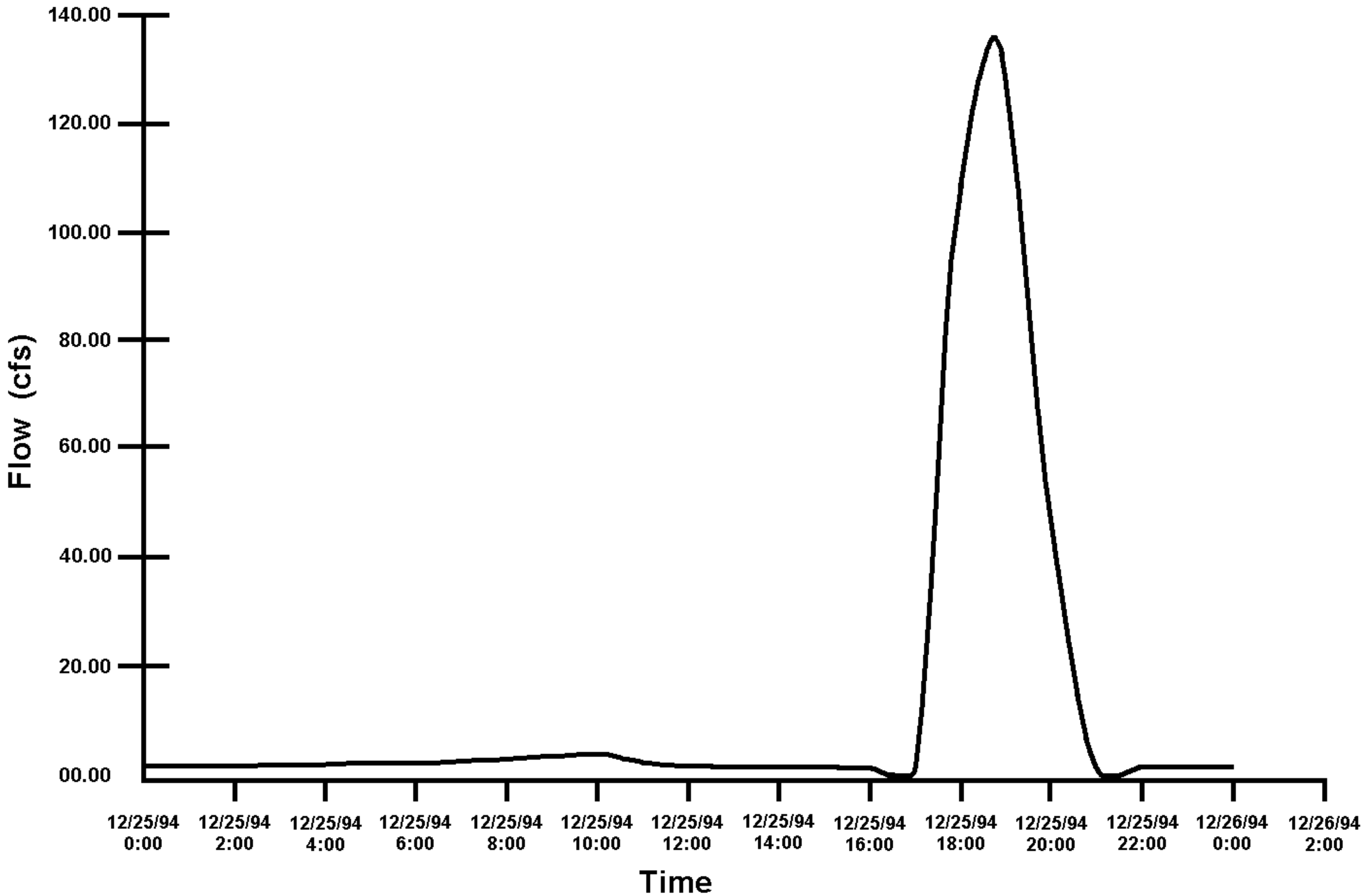

Figure 9-18. Flow in Boulder Creek at the Orodell gauging station, December 25, 1994.

Recognition of this problem and the concomitant desire to restore Boulder Creek led the City to embark on an aggressive program to increase low flows in BCW. After five years of negotiations, the City was able to transfer its water rights to provide a minimum flow of 15 cfs in Middle Boulder Creek and minimum flows in other parts of the BCW system. This water will be available for instream flow needs in all but the most serious droughts. If such a drought occurs, the City can use this water for essential water needs. The present value of these water rights transfers is about $14 million, a significant investment for the City of Boulder.

Understandably, restoring base flows for instream needs is the top priority for a stream restoration program. This water is of excellent quality. The next steps include:

1. Improved monitoring to verify that these instream flows are being maintained.
2. Improved accounting methods for tracking water movement through BCW.
3. Reducing extreme flow variability from pulsed hydropower releases.
4. Obtaining more capacity in Barker Reservoir to better manage instream flow needs in Middle and South Boulder Creeks.
5. Increased attention to water quality management along with water quantity and land management. Nonpoint pollution appears to be the most pressing concern.

Stream restoration is a vital part of the instream flow augmentation program. The required flows to support various instream activities depends upon the nature of the stream. If the stream has been channelized into a trapezoidal cross section, then it is not as desirable from a fishing or boating point of view. With a restored stream system with ripples and pools, the minimum required flow is about three to five cfs whereas it is about 15-20 cfs without stream restoration. Similarly, the kayaking course with restoration requires significantly less flow (20-30 cfs) instead of more than 100 cfs without restoration (Lacy 1995).

Importation of Water

Boulder Creek receives imported water from the Colorado-Big Thompson Project. This water is delivered to Boulder Reservoir north of Boulder. Some of this water is used by the City of Boulder with the balance directed to other users. The Boulder Supply Canal transfers water from Boulder Reservoir to Boulder Creek just upstream of the Wastewater Treatment plant. This water provides a major increase in the streamflow during the warmer months of the year.

Overall Water Budget for Boulder

In order to understand integrated watershed management, a fairly complete water budget for the urban area is essential (McPherson 1973). Calendar year 1992 was chosen because of the availability of data. It was a drier than average year. The key sources and sinks of the water budget are discussed first followed by presentation of annual, monthly, daily, and hourly water budgets.

Sources

1. Boulder Creek at Orodell: This input is measured by a USGS gage. The Orodell station is downstream of North Boulder Creek and therefore includes this source. The natural flow at Orodell has been significantly altered by upstream diversions for municipal water use.

2. Fourmile Creek: This input is measured by a USGS gage.

3. South Boulder Creek: This input is not measured. It is assumed to be zero. Except in wetter years, the entire flow in South Boulder Creek is utilized for needs of area inhabitants.

4. Urban Runoff: This input is estimated based on a very rough estimate of contributing land use. The estimate will be updated with better data.

5. Wastewater Treatment Plant: This input is measured. A significant part of the wastewater flow is infiltration and inflow.

6. Boulder Reservoir: Deliveries to Boulder Creek to satisfy downstream water users. This inflow enters Boulder Creek just upstream of the wastewater treatment plant near 75th St.

Sinks

1. Diversions: These diversions occur at Canyon Mouth, Broadway, and along Boulder Creek between Broadway and 75th St. These data are obtained from the State Engineer's office.

2. Boulder Creek at 75th St.: These are measured flows at a USGS gage.

Annual Water Budget

The annual water budget for calendar year 1992 is shown in Table 9-9 and Figure 9-19. The total estimated sources entering Boulder Creek above 75th St. are the upstream flow of 54.55 cfs, the wastewater treatment plant return flow of 26.98 cfs, the Boulder Supply Canal imported water from the CBT project of 29.29 cfs, and the estimated stormwater runoff of 7.2 cfs. Urban runoff is estimated to be 6.17 cfs out of the total of 7.2 cfs of local runoff. A simple rainfall-runoff relationship was used to estimate the runoff. This simple method was used since the data on land use and imperviousness are only approximate. Also, no direct rainfall-runoff measurements are available.

The sinks of water are the diversions from Boulder Creek. The total of diversions for calendar year 1992 was 36.64 cfs averaged over the entire year. Most of these diversions occur during the irrigation season. This water budget ignores groundwater influences since no data are available. Also, the inflow from South Boulder Creek is estimated to be zero for 1992, a relatively dry year.

Of all of the above items, only the runoff is estimated. All of the other items in the water budget are measured. The overall result of the annual water budget is an estimated total sources of 118.0 cfs and total outflows of 120.9 cfs, leaving unaccounted for a total of 2.9 cfs of inflow. This inflow is some combination of stormwater runoff and groundwater inflow. Lacking better measurements, the nature of this residual is unknown.

The error in the annual water budget is less than 3%. Thus, some statements can be made about the expected relative importance of urban runoff. Urban runoff averages about six cfs over the entire year. By comparison, the WWTP effluent is 26.98 cfs, over four times larger. Of course, urban runoff occurs infrequently (about 2% of the time). Thus, it takes on greater relative importance when it does occur.

Monthly Water Budget

The monthly water budget for CY 1992 is shown in Table 9-10 and is plotted on Figure 9-20. The errors are random. The predictions follow the measured outflow fairly closely. The monthly budgets reflect flow in Boulder Creek at 75th St., the downstream boundary of the City. The flows within the City are significantly less since the Boulder Supply Canal and the WWTP provide major inputs of water. The estimated monthly flow within the city (at 28th St.) is shown in Table 9-11 and the associated time series is shown in Figure 9-21. Much of the inflow to the city is diverted above 28th St. however, most of the urban runoff enters Boulder Creek downstream of the city. Thus, the relative importance of urban runoff is still small as shown in Table 9-10.   Prevailing average monthly flows at 28th St. during the late summer and early fall are in the 10 to 20 cfs range.

Table 9-9. Overall water budget for calendar year 1992 (flow in cfs).

Sources, Average Flow Rate				
		Urban	Other	
1	Sunshine	0.00	0.08	
2	Urban Runoff 1	0.29		
3	Gregory	0.28	0.08	
4	Urban Runoff 2	0.65		
5	Bear Creek	1.29	0.27	
6	Urban Runoff 3	0.11	0.01	
7	Goose Creek	2.03	0.08	
8	Urban Runoff 4	0.40	0.01	
9	Wonderland C.	0.38	0.06	
10	Fourmile C.	0.69	0.40	
11	WWTP	0.06	0.03	
Total Urban & Other Runoff		6.17	1.03	
Total Runoff			7.20	
Upstream			54.55	
WTP off			26.98	
Bo. Sp. Canal			29.29	
Total Source				118.02
Sinks, Average Flow Rate				
1	Anderson	501	3.97	
2	Boulder Lefthand	513	2.43	
3	Boulder White Rock	516	9.59	
4	Farmers	525	7.48	
5	Green	528	2.71	
6	Silverlake	603	1.23	
7	Butte Mill	518	2.11	
8	N. Boulder Farm	543	7.10	
Total Sinks				36.64
Computed Flow (sources-sinks)				81.38
Observed Flow @ 75th gage				84.24
Residual (observed-computed)				2.86

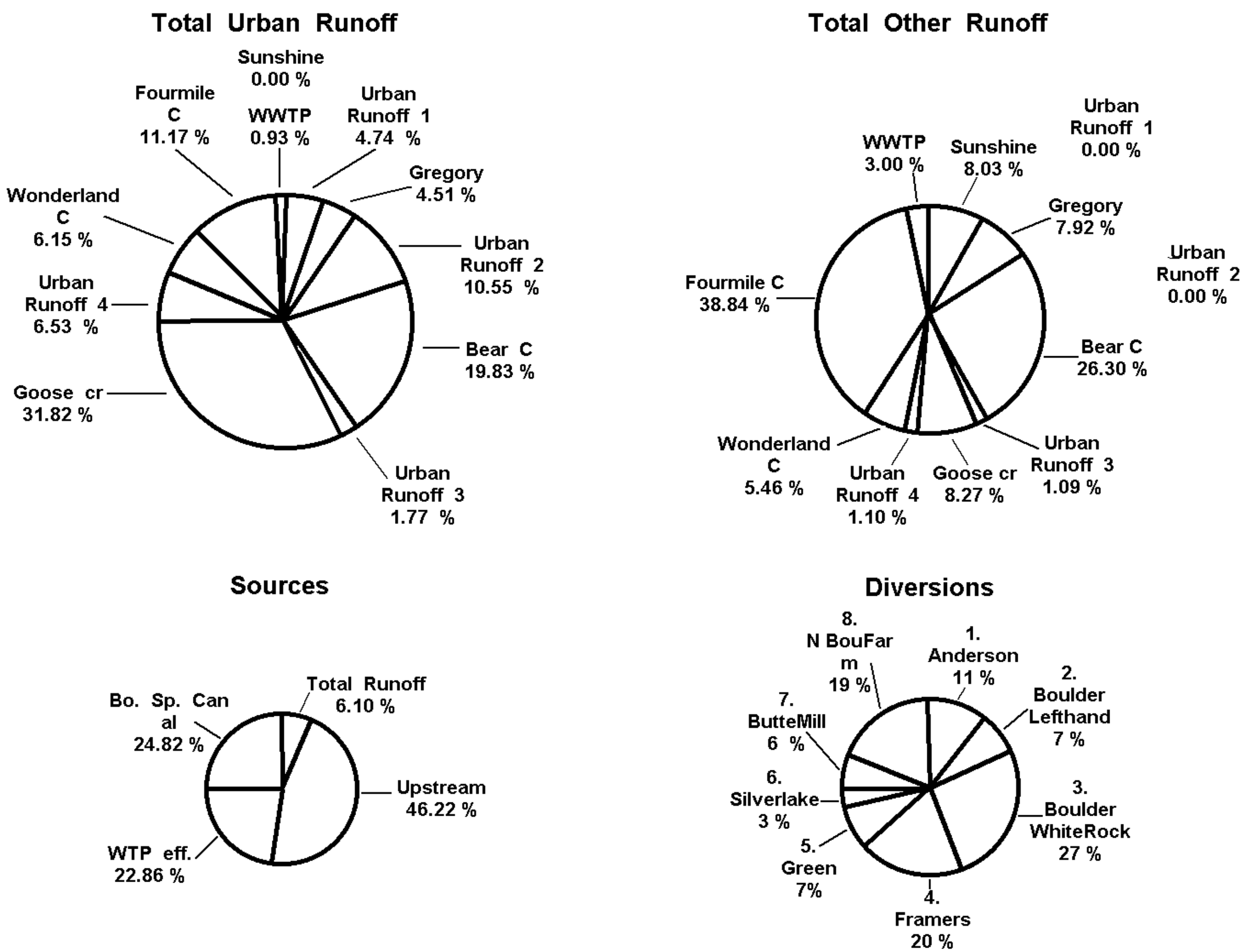

Figure 9-19. Overall water budget for calendar year 1992.

Table 9-10. Measured and computed monthly flowrates in 1992.

Month	Average Flow (cfs)			Residual as % Of Computed
	Computed	Observed	Residual	
Jan	38.45	40.74	-2.30	-6
Feb	38.94	34.28	4.67	12
Mar	72.74	71.71	1.03	1
Apr	62.79	83.47	-20.68	-33
May	125.03	135.35	-10.33	-8
Jun	101.63	127.13	-25.51	-25
Jul	182.38	192.35	-9.97	-5
Aug	149.47	140.52	8.96	6
Sep	43.79	50.77	-6.97	-16
Oct	49.75	41.13	8.62	17
Nov	54.35	37.70	16.65	31
Dec	52.69	48.52	4.17	8

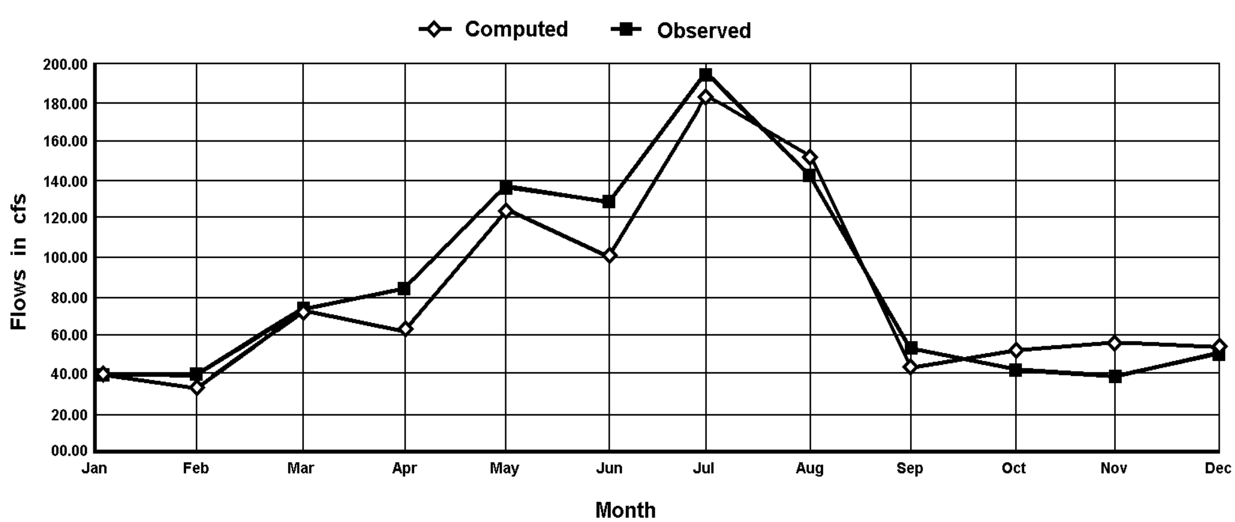

Figure 9-20. Boulder Creek monthly flows in 1992.

Table 9-11. Monthly flows in Boulder Creek at 28th St. for calendar year 1992.

	Month											
	Jan-92	Feb-92	Mar-92	Apr-92	May-92	Jun-92	Jul-92	Aug-92	Sep-92	Oct-92	Nov-92	Dec-92
Sources (cfs)												
Sunshine	0.03	0.00	0.30	0.02	0.10	0.04	0.05	0.17	0.00	0.04	0.17	0.05
Urban Runoff 1	0.09	0.00	1.08	0.07	0.37	0.14	0.19	0.62	0.00	0.15	0.59	0.18
Gregory Urban	0.09	0.00	1.03	0.07	0.35	0.13	0.18	0.59	0.00	0.14	0.56	0.17
Other	0.03	0.00	0.30	0.02	0.10	0.04	0.05	0.17	0.00	0.04	0.16	0.05
Urban (Runoff 1 & Gregory)	0.18	0.00	2.11	0.14	0.72	0.28	0.37	1.21	0.00	0.29	1.15	0.34
Urban Runoff & Other	0.23	0.00	2.72	0.18	0.92	0.36	0.48	1.56	0.00	0.38	1.47	0.44
Upstream	13.67	16.20	21.96	54.57	137.90	133.30	109.77	69.13	33.63	23.45	15.03	24.06
Total Sources	13.90	16.20	24.68	54.75	138.83	133.66	110.25	70.69	33.63	23.83	16.50	24.50
Sinks (cfs)												
501 Anderson	0.00	0.00	5.69	11.76	6.58	6.54	5.87	4.02	3.66	3.23	0.00	0.00
513 Boulder Lefthand	0.00	0.00	0.00	1.94	8.61	11.47	1.95	3.23	1.70	0.33	0.00	0.00
516 Boulder Wrock	0.00	0.00	0.00	7.85	37.22	45.03	22.92	1.97	0.00	0.00	0.00	0.00
525 Farmers	0.00	0.00	0.00	0.00	11.68	26.63	29.51	16.51	4.99	0.00	0.00	0.00
526 Green	0.00	0.00	0.00	0.00	5.87	6.92	5.99	8.18	3.78	1.65	0.00	0.00
603 Silverlake	0.00	0.00	0.00	0.00	1.80	3.58	3.90	3.02	2.47	0.00	0.00	0.00
543 N. BouFarm	0.00	0.00	0.00	0.70	16.19	19.58	23.82	15.70	7.57	1.22	0.00	0.00
Total Sinks	0.00	0.00	5.69	22.25	87.96	119.75	93.96	52.63	24.17	6.43	0.00	0.00
Flow at 28th Street	13.90	16.20	16.27	32.50	50.87	13.91	16.29	18.06	9.46	17.40	16.50	24.50

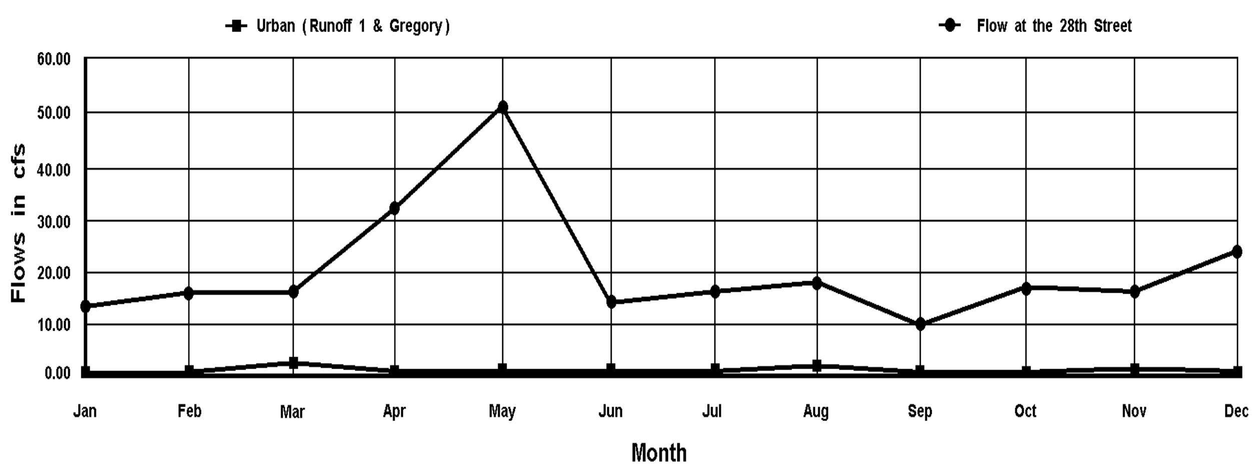

Figure 9-21. Monthly flows in Boulder Creek at 28th St. for calendar year 1992.

The results of the monthly water budget show the dramatic influence of human activities on the flows in Boulder Creek. The 1992 monthly flows above the City of Boulder, within the City of Boulder, and downstream of the City of Boulder are shown in Table 9-12 and Figure 9-22. The streamflows differ dramatically. The inflow above the city is diverted before the stream moves through much of the city. The flow downstream of the city is over four times larger due to water import and the wastewater return flow. Thus, three distinctly different hydrologic environments exist even though the total distance from above to below the city is only about eight miles. The upper and within the city stations are only two miles apart. The magnitude of the human-induced sources within the Boulder study area are shown in Table 9-13 and Figure 9-23. The wastewater treatment plant return flow is relatively constant at 26.97 cfs. However, the diversions and imports vary widely with virtually all of these flows occurring during the irrigation season. On an annual average, the diversions are the largest component followed by the imports. Recall that the estimated urban runoff is about six cfs, far less than these values.

Daily Water Budget

Lastly, a daily water budget was done for calendar year 1992. The results are summarized here. The predicted versus measured flows track fairly well. Notable differences occur during storm periods, especially in the colder months, when the precipitation is actually snow with entirely different runoff patterns. Critical water quality conditions occur during the late summer and early fall so attention was focused on these months. The August results indicate that the maximum actual daily flow at 75th St. was 250 cfs, one half of the predicted maximum flow of 500 cfs. This peak was in response to the largest single rain event of the year. Typical flows decreased from about 200 to 50 cfs over the month. The dominant terms in the water budget for August are the import and export of water for irrigation. Urban runoff is still a relatively small amount. Boulder Creek flows continued to decrease in September to about 40 cfs. During October, the main source of flow in the stream is the WWTP return flow. The Boulder Supply Canal deliveries declined as the irrigation season began to end.

Hourly Water Budget

Only a few cfs of flow are available in Boulder Creek as it passes through the city in late summer and early fall. However, it is important to understand the water budget, not only on a daily basis, but also to do an hourly accounting. From October to March, PSCO releases water to Boulder Creek in pulses for hydropower peaking purposes during the early evening hours. Thus, while the average daily inflow might be 10 to 15 cfs, the actual flow pattern is 140 cfs for two to three hours and zero flow the rest of the day as shown in Figure 9-18. Thus, the fish in Boulder Creek must adapt to very wide swings in flow even on an hourly basis. Similar conditions would occur in other streams where hydropower is generated. Such extreme daily flow swings would tend to have a more significant impact on the fish than urban runoff because of their much greater frequency.

Table 9-12. Monthly flows in Boulder Creek for calendar year 1992, above, within and below the City of Boulder (in cfs).

Month	(1)	(2)	(3)
	Mean Monthly Flows in Boulder Creek, 1992		
	Above Boulder	Within Boulder	Below Boulder
Jan-92	13.67	13.90	40.74
Feb-92	16.20	16.20	34.28
Mar-92	24.68	16.27	71.71
Apr-92	54.75	32.50	83.47
May-92	138.83	50.87	135.35
Jun-92	133.66	13.91	127.13
Jul-92	110.25	16.29	192.35
Aug-92	70.69	18.06	140.52
Sep-92	33.63	9.46	50.77
Oct-92	23.83	17.40	41.13
Nov-92	16.50	16.50	37.70
Dec-92	24.50	24.50	48.52
Average	55.10	20.49	83.64

1. Measured flow above Boulder. Stream mile = 25.5.
2. Estimated flow at 28th St. Stream mile = 23.5.
3. Measured flow below Boulder at 75th St. Stream mile = 17.5.

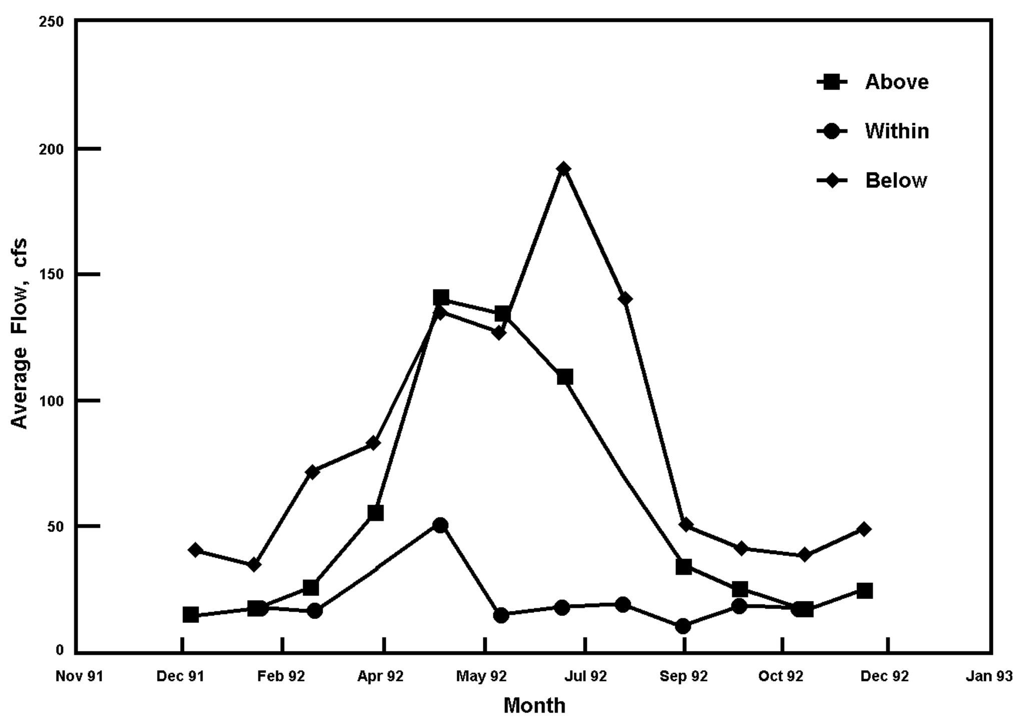

Figure 9-22. Monthly flows in Boulder Creek for calendar year 1992, above, within, and below the City of Boulder.

Table 9-13. Total sources of flow, Boulder Creek, CO, 1992 (in cfs).

Month	Local		Total Runoff	Upstream Inflow	WWTPeff	BsupCanal	Total Sources	Runoff (%)	Runoff Producing Rainfall (inches)
	Urban Runoff	Other Runoff							
Jan	1.94	0.32	2.26	13.67	22.51	0.00	40.71	4.77	0.41
Feb	0.00	0.00	0.00	16.20	22.74	0.00	38.94	0.00	0.00
Mar	22.83	3.79	26.62	21.96	29.81	0.03	105.05	21.73	4.82
Apr	1.52	0.25	1.77	54.57	28.35	0.35	86.80	1.75	0.31
May	7.77	1.29	9.08	137.90	27.58	45.40	229.01	3.39	1.84
Jun	2.99	0.50	3.48	133.30	28.79	62.47	231.52	1.29	0.61
Jul	4.03	0.67	4.70	109.77	29.16	137.97	286.29	1.41	0.85
Aug	13.12	2.18	15.30	69.13	29.96	91.65	221.34	5.93	2.77
Sep	0.00	0.00	0.00	33.63	28.98	7.72	70.33	0.00	0.00
Oct	3.17	0.53	3.70	23.45	26.51	2.51	59.88	5.30	0.67
Nov	12.38	2.06	14.44	15.03	24.88	0.00	68.79	18.00	2.53
Dec	3.69	0.61	4.31	24.08	24.31	0.00	57.00	6.48	0.78

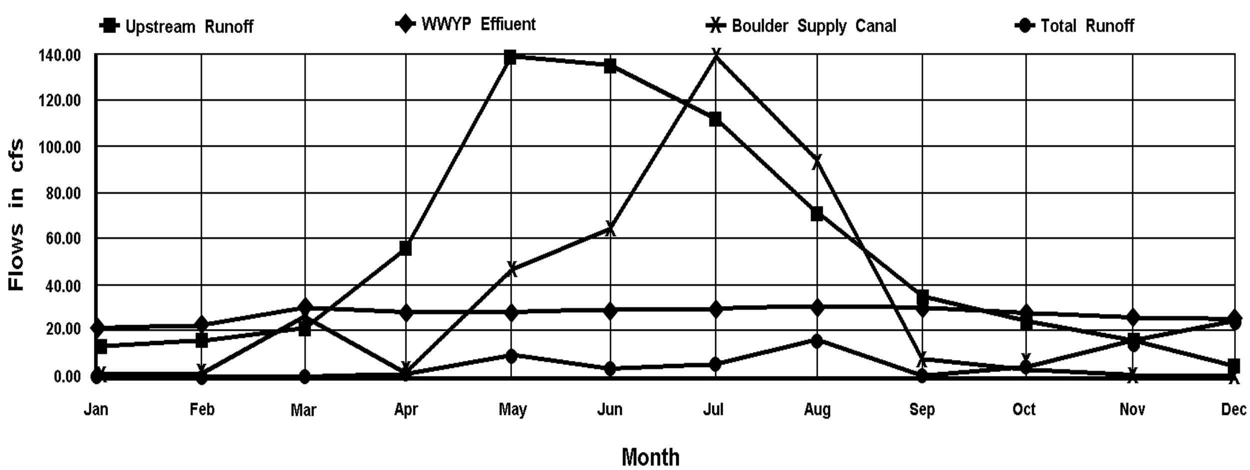

Figure 9-23. Total sources of flow for Boulder Creek, CO, 1992.

Conclusions Drawn from the Water Budget

The results of examining the behavior of Boulder Creek each hour of calendar year 1992 provide dramatic testimony to the influence of man on this stream. Boulder Creek is typical of streams in urban areas because of the intense level of human activities associated with manipulating water resources as part of agricultural, industrial, mining, urban and/or other activities. The following conclusions can be drawn from this water budget:

1. Given the wide variability in flows, even from hour to hour, it is not meaningful to try to find a single "design event" to analyze the impact of urban runoff or any other single term in the water budget.

2. A continuous water budget with a small time step, that is, hourly, is essential in order to capture the reality of stream dynamics.

3. A process oriented approach is essential to accurately characterize what is happening in complex urban stream systems. The Boulder Creek system has evolved over the past 139 years and is a complex combination of facilities and processes including reservoirs, canals, hydropower generation, imports, exports, and instream flow releases. Statistical approaches can be used in conjunction with continuous simulation but a process oriented continuous simulation is essential in order to derive reliable information for risk analysis.

4. A primary purpose of human activities is to reduce the variance in streamflows. The prior appropriations doctrine used in the West allows human activities to be traced and to show how variance reduction occurs due to deliberate human actions.

5. The hydrologic regime changes drastically over the eight mile reach of Boulder Creek as it passes through Boulder. Thus, it is not meaningful to base policy decisions on average conditions. The stream goes from being a rushing mountain stream used for kayaking to a gentle valley stream flowing through open space. Thus, the desirable flow regime varies accordingly.

6. Fish are permanent residents of Boulder Creek. Thus, from their perspective, the flow frequency analysis should be done with a very short time step, say an hour. Existing water quality standards, based on a seven day average low flow, have little meaning to a fish population that has to live in a stream system with flows ranging from 0 to 140 cfs over a single day.

7. The wide variety of stakeholders associated with Boulder Creek continue to adapt the stream system and its management in light of changing attitudes and values. The Boulder Greenways Program, implemented during the past decade, is a dramatic example of these changes as is the City's recently enacted instream flow improvement program.

8. Population and land use management via the open space program have had a major beneficial impact on Boulder Creek. Thus, an integrated appraisal of land and water management is essential.

9. A risk analysis-based approach to the problem can be easily implemented using the results of the continuous simulation model. The frequency distributions need to reflect the appropriate averaging time for the affected species. For Boulder Creek, an hourly time step is essential because of the dynamics of the forcing functions on the system and the short travel times through the system.

Urban Stormwater Quality

Stormwater Pollution in Boulder

The City of Boulder inventoried nonpoint pollution sources within BCW (City of Boulder 1990). Results are summarized here under the headings of agricultural, forest fires, highway, mining and urban runoff.

Agricultural Water Quality

Irrigation using Boulder Creek water is practiced in the lower valley portion of BCW. Irrigation return flows and nonpoint runoff do not have a significant impact on Boulder Creek above 75th St. because this agricultural water enters downstream. Agricultural activities may impact water quality entering Boulder Reservoir.

Forest Fires

A large 4.5 square mile fire occurred during the summer of 1989 in the foothills area called Sugarloaf Mountain. Subsequent heavy rains caused severe soil erosion in the immediate area. Some of these impacts were felt in Boulder Creek with additional sediment accumulations of up to 16 inches.

Highway Runoff

Sanding and salting of highways during the winter months increase loadings to the BCW. Highway 119, which runs parallel to Middle Boulder Creek, is one of the prime concerns due to the relatively heavy traffic and need for extensive ice control due to its mountainous location. During the winter of 1987-1988, a total of 2,869 tons of sand and 201 tons of salt were applied to 17 miles of Highway 119 between Nederland and the canyon mouth. An equivalent amount is applied to county roads that intersect Highway 119. No specific detrimental receiving water impacts have been documented to occur as a result of this activity.

Mining Runoff

BCW was once actively mined. Some residual mine runoff occurs. Gravel mining in the lower portions of BCW has also had an impact on the creek. These problems have been addressed. Some runoff quality problems from mining still exists during relatively wet periods, such as 1995.

Urban Stormwater Quality

Nilsgard (1974) evaluated urban runoff in Boulder. He sampled an urban catchment that drained to Boulder Creek near Broadway. Nilsgard noted the impact of stream diversions on flows in the system. During dry-weather periods, virtually all of the streamflow was diverted at Broadway just above where the storm drain entered Boulder Creek. Base flow in the storm drain provided the only significant dry-weather flow in Boulder Creek at that point. Nilsgard's data showed that urban runoff is equivalent to secondary effluent based on annual loads were calculated. Unfortunately, Nilsgard did not explain how urban loads were calculated. In contrast, analysis completed for this report indicates that urban runoff is much less important than sewage effluent on an annual basis.

Bennett and Linstedt (1978) analyzed Boulder's stormwater quality with a limited sampling program of an urban, suburban, agricultural, and natural area. They sampled six storm events, most of which reflected winter snow conditions. Their results indicate that urbanization appears to cause a decrease in water quality. They did not relate the variable water quality to any beneficial uses. They also looked at treatability. Bennett and Linstedt (1978) concluded that more studies are needed to understand the quality of urban runoff and its impact on the receiving water.

Deacon and Vaught (1993) sampled Boulder Creek upstream of the City (Orodell), in the city (Library and Scott Carpenter Park), and downstream (Valmont). Boulder Creek was sampled in 1991 on April 23, May 30, July 31, September 27, December 6, and on February 4, 1992. All of their results indicate a healthy aquatic environment in Boulder Creek. Unfortunately, they did not describe the flow in the stream nor whether the sampling was related to storm events.

The City of Boulder Stormwater Quality group has been monitoring water quality in Boulder Creek for the past few years. Also, all of the over 1,000 outfalls into the Boulder Creek stream system have been inventoried and checked for dry-weather flows. Generally, Boulder’s stormwater runoff is typical of other urban areas. No significant illicit sources of storm drainage were identified.

Urban stormwater quality can be estimated using event mean concentration estimates, which are based on a national database for the U.S. (Debo and Reese 1994). Also, Denver has collected many samples of urban runoff quality as part of earlier studies of the nature of urban runoff (NURP studies) and more recent NPDES sampling. Boulder has also collected urban runoff quality samples. The national and Denver databases of stormwater samples for suspended solids concentrations were evaluated to see how these concentrations vary both spatially and temporally. A comparison of the means and variances of the two datasets indicates no significant differences in the means or the variances.

The main controls for urban runoff and nonpoint runoff control in Boulder have been a very aggressive land acquisition program, which has set aside about 60,000 acres during the past 25 years. This open space program has the concomitant objective of limiting population growth in the City of Boulder to 160,000 people instead of the earlier projection of 250,000, a 36 % reduction in projected population. Another control is the Tributary Greenway Program wherein the City has acquired riparian lands and created an award winning linear park and greenbelt system, which is heavily used by residents and visitors. A major stream restoration was done as part of this program. The key direct water related component of this study was the City's commitment for instream flow needs with a guaranteed minimum flow of 15 cfs in Middle Boulder Creek as it moves through the City. The City has also installed stormwater detention systems to reduce pollutant loads from some of its tributaries such as Goose Creek. These ponds are an integral part of the Greenway program.

More complete analysis of Boulder's urban runoff quantity and quality is limited by the lack of concurrent measurements of flow and quality from the major storm drains and tributaries. The results of stormwater quality sampling indicate no major problems nor is there any direct evidence of the link between urban runoff and stream impairment, (e.g., fish kills). The City plans to install additional stream gages along Boulder Creek. This will greatly improve the accuracy of estimates of the relative importance of urban runoff.

Recreation and Water Quality in Boulder Creek

Water quality has not been an impediment to recreation in Boulder Creek. The quality is considered to be excellent and much use is made of the stream for kayaking, tubing, and wading. The stream is not used for swimming due to its high velocity, cold temperature, and shallow depths.

Wastewater Characteristics

An important question in analyzing dry and wet-weather quality management strategies is to determine the relative importance of dry- and wet-weather sources. At the most aggregate level, the annual loads from each of these sources can be estimated to obtain the net load after adjusting for removal by treatment. An important question is to characterize the relationship between WWTP flow and concentration. If infiltration and inflow are "pure water," then a straight dilution effect would result.

Brown and Caldwell (1990) present monthly influent data for the Boulder WWTP for the period from CY 1982 to CY 1985. The influent concentration of BOD as a function of WWTP flow are shown in Figure 9-24. The negative relationship shows that concentration decreases as flow increases.

Load as a function of flow is plotted in the upper part of Figure 9-24. The resulting scatter plot indicates that the total load of BOD remains constant at higher flows. This result indicates that, for BOD, a direct dilution effect is occurring. Thus, the added infiltration and inflow are of less concern since they are not causing any significant increase in the BOD load. Figure 9-25, which is a similar plot for SS, reveals a negative correlation but a slight increase in load as flow increases. Thus, the increased flows do cause an increase in the solids load for the WWTP which may cause problems as flows continue to increase.

During the spring of 1995, a major wet weather period occurred with minor flooding and some sewer surcharging. The daily influent flows to the Boulder WWTP from 1990 to June 1995 are shown in Figure 9-26. Influent flows reached over 45 mgd, well beyond any inflows experienced prior to 1995. The WWTP was able to treat all flows without bypassing.

The relationship between WWTP flows and influent quality for BOD are shown in the lower part of Figure 9-24. The concentration decreases sharply as flow increases with influent BOD's dropping from about 250 mg/l at lower flows to less than 50 mg/l at the higher flows. The correlation coefficient for the flow-BOD relationship is -0.82. BOD load as a function of flow during this critical period is shown in the upper part of Figure 9-26. It shows that BOD load remains constant. Thus, the infiltration is simply "clean water" and provides a direct dilution effect.

The results for suspended solids are similar. Figure 9-25 shows the negative correlation coefficient of -0.55 with influent SS concentrations dropping from nearly 300 mg/l to less than 100 mg/l at higher flows. For SS, the loads appear to be constant up to a flow of about 30 mgd. However, beyond 30 mgd, the loads appear to increase significantly, probably as a result of direct inflow of water to the sewers from surface sources.

This negative correlation is of critical importance in evaluating the impacts of wastewater and urban runoff discharges on the receiving water. The negative covariance greatly reduces the potential impact since there is a strong dilution effect as flow increases.

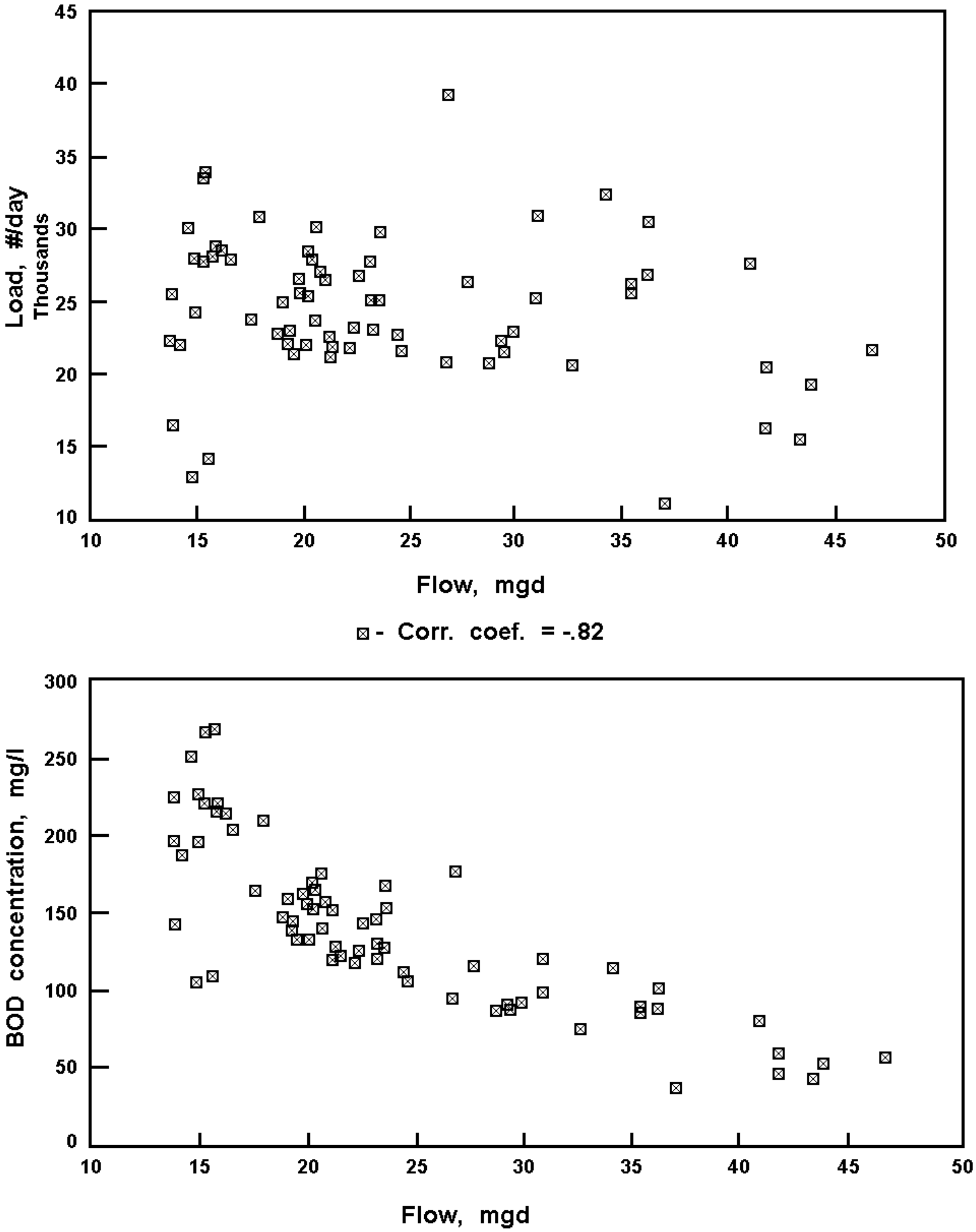

Figure 9-24. Effect of flow on BOD load and concentration, Boulder WWTP, 1990-1995.

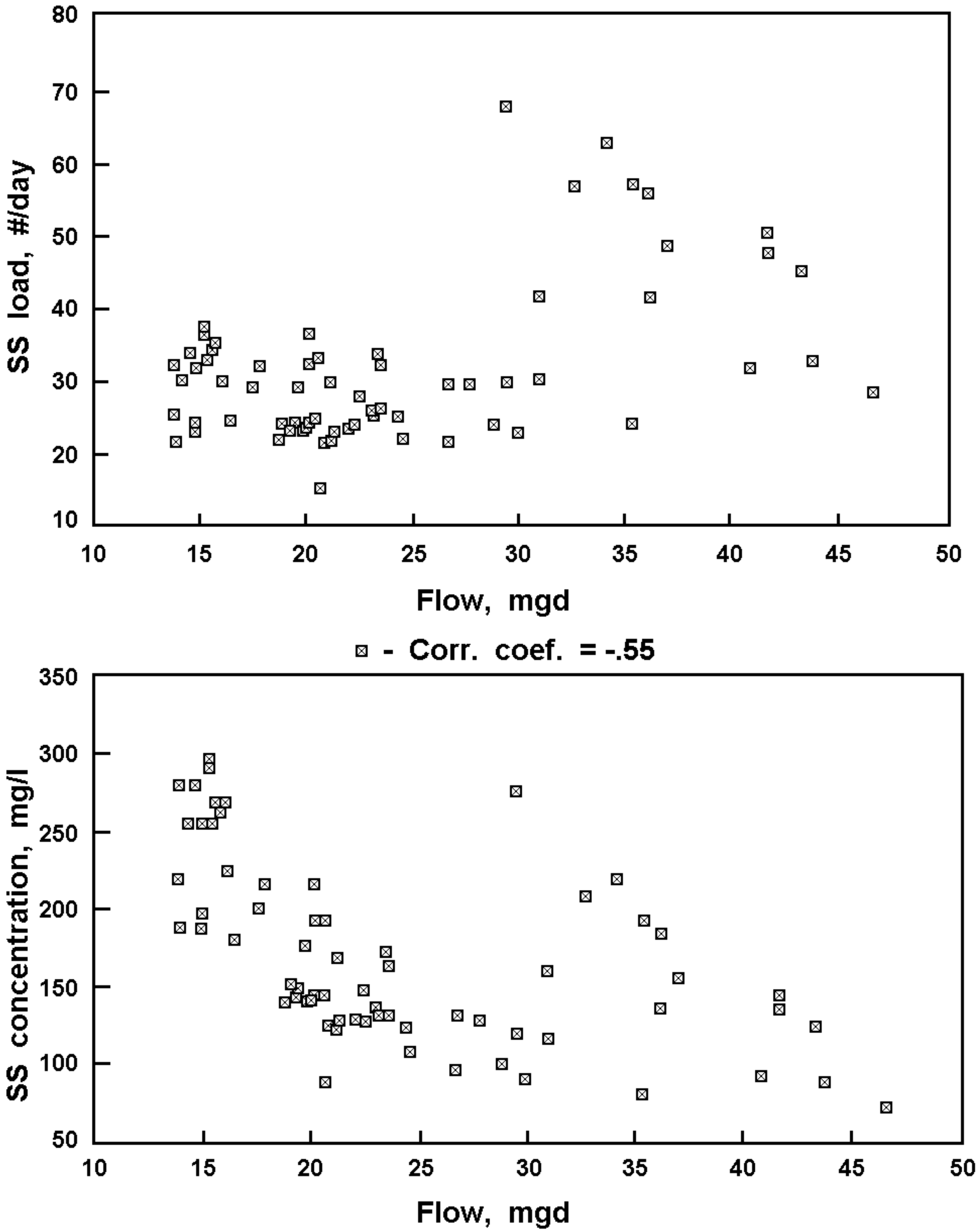

Figure 9-25. Effect of flow on SS load and concentration, Boulder WWTP, 1990-1995.

Removal Efficiencies

The removal efficiencies for the Boulder 75th St. WWTP during 1984 and 1985 were as follows (B&C 1990):

Constituent	Primary	Primary + Secondary
BOD	41%	80%
SS	52%	80%

Removal efficiencies have improved significantly during the past five years as shown in Table 9-14. In 1988, BOD and SS removal efficiencies were about 80 %, the same as the mid-1980s performance. However, since 1989, treatment efficiencies have improved to 1994 removal efficiencies of 93.5% for BOD and 96.6 % for suspended solids, a significant improvement.

Current (1994) variability in treatment plant performance is quite low as shown in Table 9-15. The effluent SS and BOD show very consistent concentrations with coefficients of variation (standard deviation/mean) of about 0.10. Even during the unprecedented wet period of spring 1995, the WWTP produced high quality effluents as shown in Figures 9-27 for SS and Figure 9-28 for BOD. The effluent BOD and SS concentrations are independent of flow rate. Thus, the Boulder WWTP is producing a uniformly high quality effluent with little variability in performance even beyond its nominal design capacity.

Sanitary Sewer Overflows

The City of Boulder has not needed to bypass any of its sanitary sewage, even during the record high flows of spring 1995. This event has a recurrence interval of about one in 25 years. Some localized surcharging of the sanitary sewers did occur for short periods. Thus, Boulder does not presently have a serious sanitary sewer overflow problem.

Overall Receiving Water Quality Impacts

The water quality standards for the State of Colorado classify waters based on the beneficial uses to be protected. The only direct water quality evaluations that have been done are the standard receiving water quality calculations to determine the expected impact of the wastewater treatment plant on Boulder Creek during the one in ten year, seven day duration low flow. This approach to water quality management is extremely narrow because it ignores all of the other components of the water budget and focuses on a single, unusual point in time. As clearly pointed out in the water budget section, the health of the stream is an integration of the continuous impacts over time.

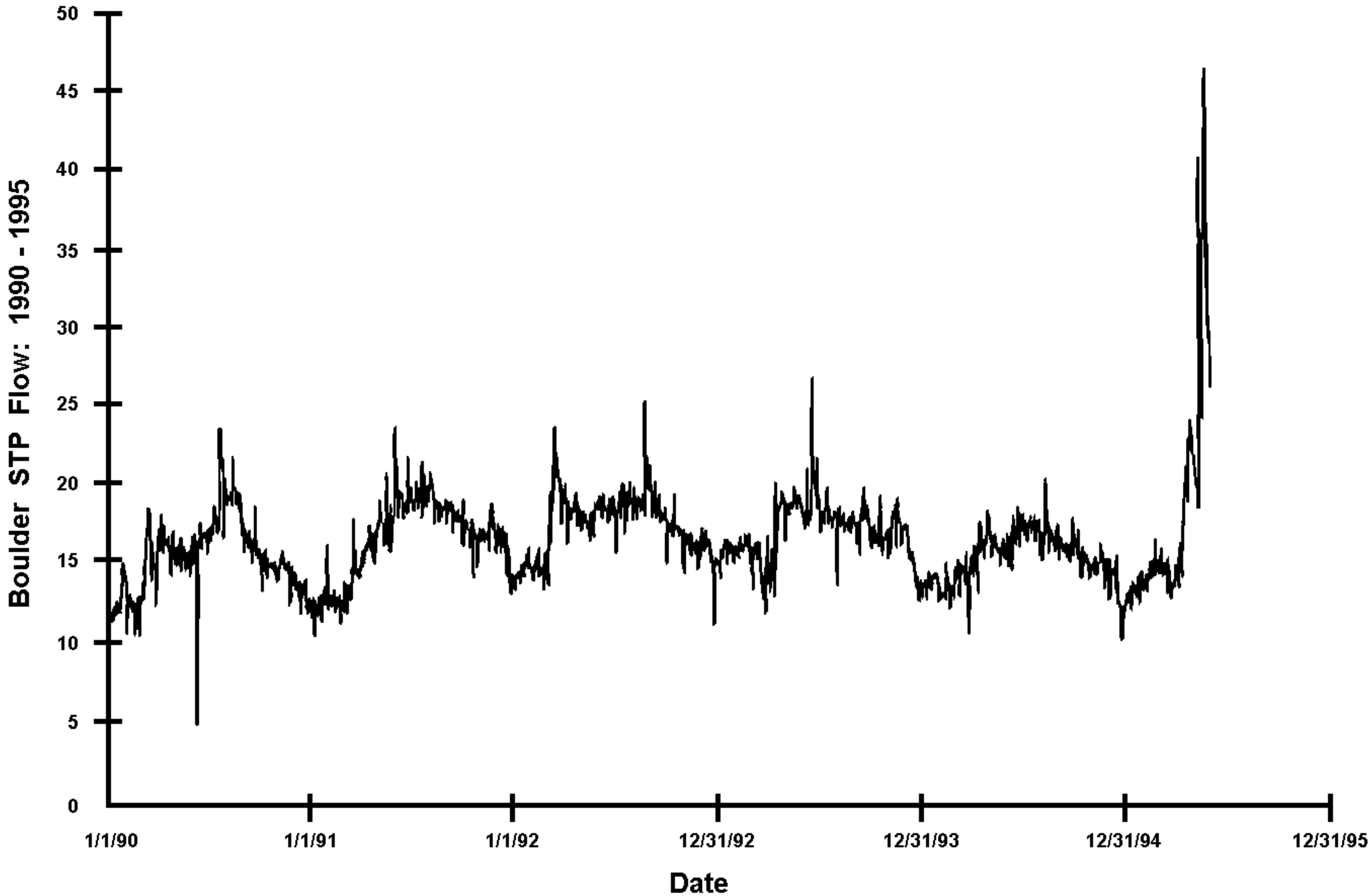

Figure 9-26. Influent flow to Boulder WWTP, 1990 – 1995.

Table 9-14. Trends in annual performance of 75th St WWTP, 1988 – 1994.

Year	Flow (mgd)	Inf. BOD (lb/day)	Inf. BOD (mg/l)	Effl. BOD (lb/day)	Effl. BOD (mg/l)	BOD Removal (%)	Inf. SS (lb/day)	Inf. SS (mg/l)	Effl. SS (lb/day)	Effl. SS (mg/l)	SS Removal (%)
1988	15.4	17036	133	3727	29.02	78.1	16981	132.21	3304	25.72	80.5
1989	15.1	16837	134	2731	21.69	83.8	15838	123.31	1946	15.15	87.7
1990	16.1	19045	142	2332	17.37	87.8	17837	138.88	1048	8.16	94.1
1991	16.5	20064	146	2520	18.31	87.4	18195	141.67	1110	8.64	93.9
1992	17.4	23942	165	1943	13.39	91.9	22635	176.24	1109	8.63	95.1
1993							26268	181	909	6	96.5
1994	15.5	23300	182	1522	10	93.5	24371	189	833	7	96.6
Permit Limit	20.5	29065					29065				

Table 9-15. Trends in monthly performance of 75th St WWTP.

Month-Yr.	Days/mo.	Flow (mgd)	Influent BOD (mg/l)	Influent SS (mg/l)	Effluent BOD (mg/l)	Effluent SS (mg/l)
Jan-92	31	14.5	171	157	24	11
Feb-92	29	14.7	174	158	21	10
Mar-92	31	19.2	134	133	13	8
Apr-92	30	18.3	146	142	13	8
May-92	31	17.8	142	140	13	8
Jun-92	30	18.6	132	126	10	10
Jul-92	31	18.8	139	155	12	8
Aug-92	31	19.3	172	162	10	4
Sep-92	30	18.7	160	166	7	4
Oct-92	31	17.1	202	163	13	7
Nov-92	30	16.1	216	195	16	7
Dec-92	31	15.7	212	183	13	7
Jan-94	31	13.80	194	176	11	6
Feb-94	28	13.40	204	178	13	7
Mar-94	31	14.30	171	159	14	7
Apr-94	30	16.20	164	170	12	6
May-94	31	16.30	137	141	13	6
Jun-94	30	16.80	169	183	11	8
Jul-94	31	17.40	180	166	11	5
Aug-94	31	17.00	183	236	10	6
Sep-94	30	16.40	171	206	12	7
Oct-94	31	15.50	186	202	11	7
Nov-94	30	15.10	206	224	12	8
Dec-94	31	13.30	218	230	12	7
	Statistics for CY 1994					
	Mean	15.46	181.92	189.25	11.83	8.67
	Max	17.40	218.00	236.00	14.00	8.00
	Min	13.30	137.00	141.00	10.00	5.00
	STD	1.39	20.98	28.86	1.07	0.85
	C of V	0.09	0.12	0.15	0.09	0.13

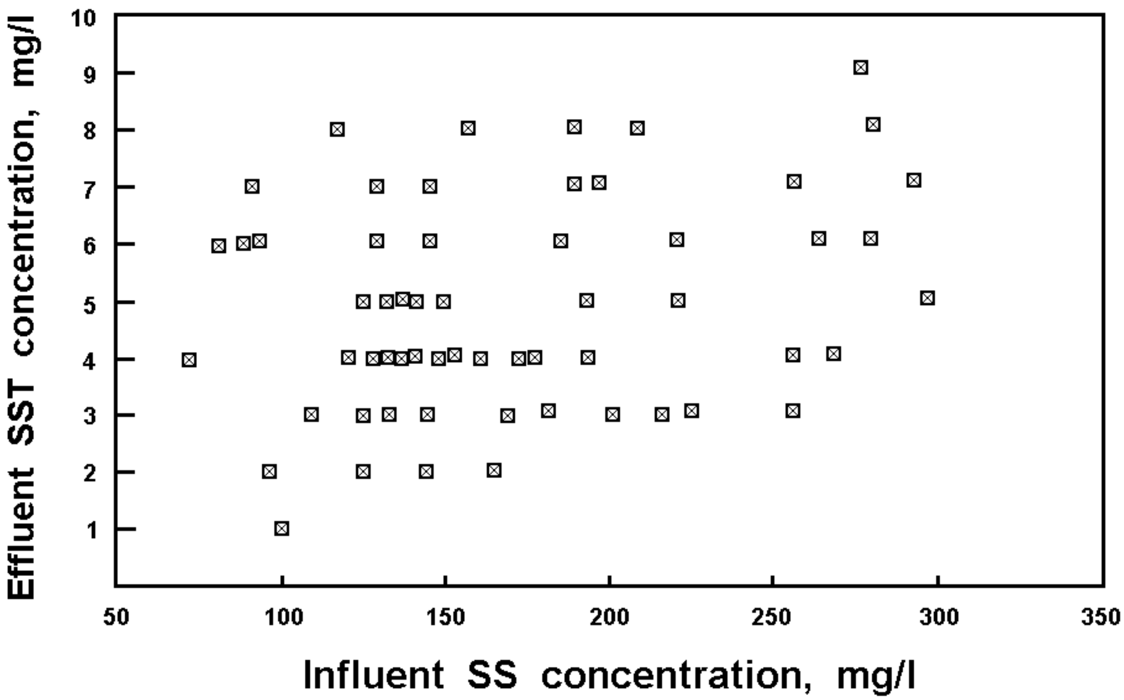

Figure 9-27. Influent vs. effluent SS concentrations, Boulder 75th St WWTP.

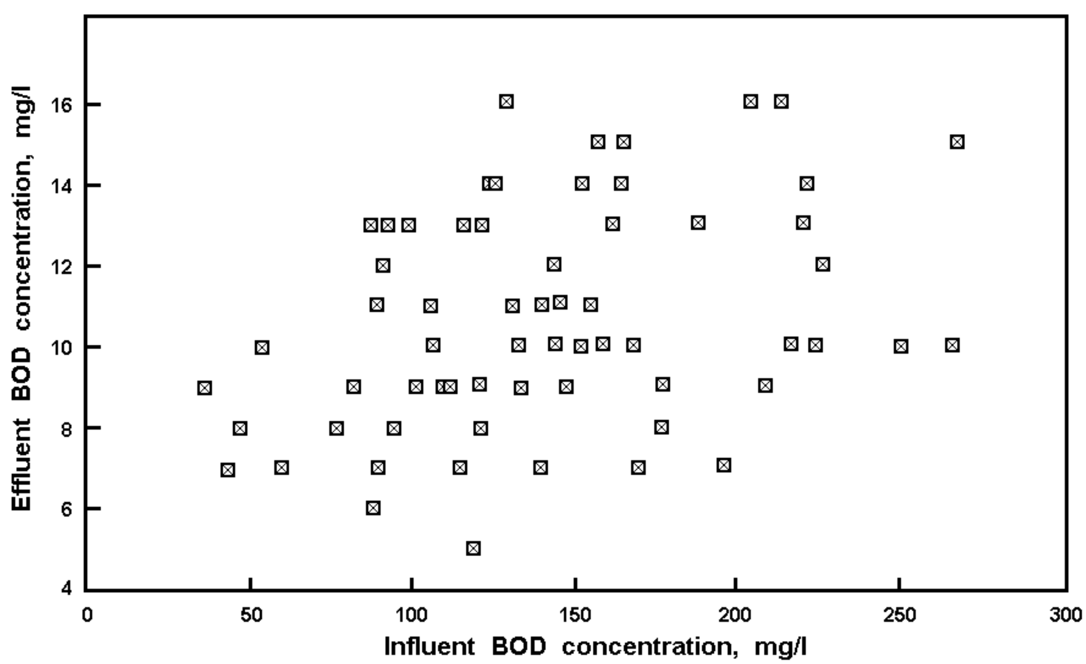

Figure 9-28. Influent vs. effluent BOD concentrations, Boulder 75th St. WWTP.

As pointed out in this case study, BCW is a complex water management system with many competing and complementary uses including water quality management. The eight mile stream section that runs through Boulder goes from a rushing mountain stream to a much slower moving valley stream. Streamflows throughout BC are heavily influenced by human activities. The upper reach is affected by storage and hydropower plant releases. The middle reach is also impacted by heavy diversions during the warmer months of the year. Lastly, the lower reach receives a major increase in flow due to water imports and the return flow from the WWTP. The potential impacts of stormwater quality on Boulder Creek are discussed here for the upper, middle, and lower sections of the creek.

Upper Section-Boulder Creek Immediately Above the City

This section of the creek does not receive any significant urban runoff. The upstream land uses are almost all natural since the land is publicly owned and managed either by the U.S. Forest Service or the City or County of Boulder. Thus, the runoff quality is excellent. Urban runoff quality does not affect this section. The major impact on this section is the upstream diversions and pulsing of flows that reduce the quantity of flow and increase the hourly variability of flows. This section of the stream is used for kayaking and was the site of the 1995 Olympic Festival kayaking competition.

Middle Section-Boulder Creek at 28th St.

This section of the creek receives urban runoff from the immediately surrounding drainage area. The concentration of this urban runoff would be typical of the reported values in the literature. Only about 20% of Boulder's urban runoff enters the middle part of the stream. This runoff is diluted by runoff from adjacent open space lands. Thus, the volume of urban runoff is relatively small. The major impact in this middle section is the greatly reduced flows in the stream because of upstream diversions as the water enters the city. Thus, less dilution water is available. The City has implemented a major program to augment these low flows and the stream has undergone restoration as part of the Greenways Program. No significant urban runoff quality problems have been reported for this reach. Intensive use is made of this section of the creek because of the creation of a Greenway about ten years ago. Current activity levels exceed one million people per year. The stream restoration recently won a national award.

Lower Section-Boulder Creek Below 75th St.

This section receives all of the urban runoff from Boulder. Some of this urban runoff has received treatment in detention systems, (e.g., Goose Creek). It also receives the return flow from the Wastewater Treatment Plant and imported water from the Colorado-Big Thompson Project. Urban runoff is a relatively small source of water, less than 25% of the WWTP effluent and only 20% of the Colorado-Big Thompson imported water. The WWTP provides a consistently excellent effluent quality even during very high flow periods such as the spring of 1995. The most sensitive time of the year for this section is early fall after the imports have ceased and when the upstream flow is low. This section of the stream is not presently accessible to the public. Thus, there is little recreational activity to report.

Risk-Based Analysis of Urban Runoff Quality

The mixed concentration of a constituent in a stream can be calculated as follows:

$$Co = (CsQs + CrQr)/(Qs + Qr) \qquad \text{Equation 9-1}$$

where Co = downstream concentration, mg/l,
Cs = upstream concentration, mg/l,
Cr = concentration of added inflow, mg/l,
Qs = upstream flow, and
Qr = added inflow.

The added inflow can be of several types including:

1. Direct urban runoff.
2. Sanitary sewer overflow.
3. Wastewater effluent.
4. Imported water.

For Boulder Creek, direct urban runoff occurs at numerous places along the stream. There are no sanitary sewer overflows. Wastewater effluent enters the stream downstream of the City as does the imported water from the Colorado-Big Thompson Project.

Analysis of the terms in Equation 9-1 and there statistical properties is critical to understanding the stream water quality impacts. The key factor which has been neglected in the literature is the covariance of concentration and flow. Covariance is defined as:

$$s(xy) = (x-xb)(y-yb) \qquad \text{Equation 9-2}$$

where $s(xy)$ = covariance between x and y,
x,y = two variables, and
xb, yb = means of x and y.

The correlation coefficient measures the extent of the covariance, or

$$r(xy) = [(x-xb)(y-yb)]/[(x-xb)^2*(y-yb)^2] \qquad \text{Equation 9-3}$$

where $r(xy)$ = correlation coefficient between x and y with
$-1 <= r <= +1$.

The expected covariance patterns for the terms in Equation 9-1 are discussed in the following:

Covariance Between Concentration and Flow

For urban runoff, if a finite amount of material is on the land surface, say a parking lot, then one would expect to see a negative covariance between concentration and flow. However, if the source of material is large, say suspended solids from a construction area, then one could indeed see a positive covariance. For most constituents, a negative covariance between concentration and flow would be expected as was observed for the WWTP influent. This negative covariance reduces the expected impacts of stormwater runoff since a dilution effect occurs.

Covariance Between Upstream Flow and Urban Runoff

The following statistics on causes of 1994 beach closings in the U.S. were reported (Water Environment and Technology 1995):

Cause	Number
Sanitary Sewer Overflows	584
Stormwater Runoff	345
Combined Sewer Overflows	194
Agricultural Runoff	136
Wastewater Treatment Plant Malfunctions	106

While beach closings is not an issue for Boulder Creek, the above statistics do give some indication of the relative importance of the various wet-weather sources and WWTP malfunctions. In the case of oceans or large lakes, the covariance between the stormwater runoff and the receiving water capacity would be expected to be zero. However, for riverine systems, one would expect it to be positive, that is, when urban runoff is entering the stream, the flow in the stream is increasing due to runoff from upstream concurrently entering the system. For Boulder Creek and the City of Boulder, the following combinations of wet-weather scenarios occur.

1. Worst Case: Localized rainfall over developed portion of the urban area only. Low base flow in the stream. This situation can occur in late summer. Thus, upstream flows would be low and most of the stream runoff would be urban runoff. This situation would be expected to happen a few times a year associated with light storms.

2. Typical Case: Moderate basin wide rainfall and runoff. This situation would be associated with the more significant storm events. In this case, the urban runoff would be a small part of the total runoff since only about 7% of the land use in BCW is urban land use.

3. Significant Wet-Weather Events: Significant wet-weather events occur one to five times per year. These events include the major flooding events, which are rarer. Under this scenario, all of BCW would be expected to be contributing flow

and infiltration entering the WWTP would be expected to be relatively high due to the wet conditions. In this case, urban runoff would be an insignificant part of the streamflow and water quality load.

Ideally, the probability density function for all of these scenarios can be developed. However, insufficient data were available to make these judgments. It is possible to show the covariance of streamflow and wastewater treatment plant flow. A total of 526 wetter days from 1990 to mid 1995 were analyzed to compare the flow in the WWTP with the flow in Boulder Creek immediately upstream of the WWTP and the imported water from the Colorado-Big Thompson project. The results, shown in Figure 9-29, indicate a strong positive covariance of streamflow and WWTP flow. The correlation coefficient is +0.81.

This covariance plot has significant implications for evaluating the impact of WWTP bypasses or overflows during wet-weather periods. Current thinking is that CSO or SSO should not occur more than a few (one to five) times per year. Thus, the system would capture and treat all of the moderate storms. During the larger storms, part, not all, of the larger events would be bypassed. How serious is this problem? If the covariance between wastewater flows and receiving water flows is determined, then one could conclude that the CSO and SSO volume is an insignificant part of the stream runoff during this very wet period.

Thus, a relatively complex combination of the joint probabilities of undesirable conditions may occur. This situation can be estimated with reliable continuous simulation or Monte Carlo analysis. The results shown in Figure 9-29 indicate 23 days when the flow in the WWTP was at least 40 cfs. This would correspond to about four events per year, well within the current guidelines of the allowable number of overflows per year. But according to the covariance analysis, if the WWTP flow is 40 cfs, then the Boulder Creek flow would be over 500 cfs, or a dilution ratio of over 14:1. At a WWTP flow of 70 cfs, the expected flow in Boulder Creek would be over 1600 cfs, a dilution ratio of over 23:1. This assumes that all of the storm is bypassed. In reality, only part of the storm would be bypassed. If the capacity of the plant was 50 cfs, then the bypass would be the difference. Thus, the expected overflow for the 70 cfs case is 20 cfs, not the entire 70 cfs. Correspondingly, the dilution ratio is about 80:1.

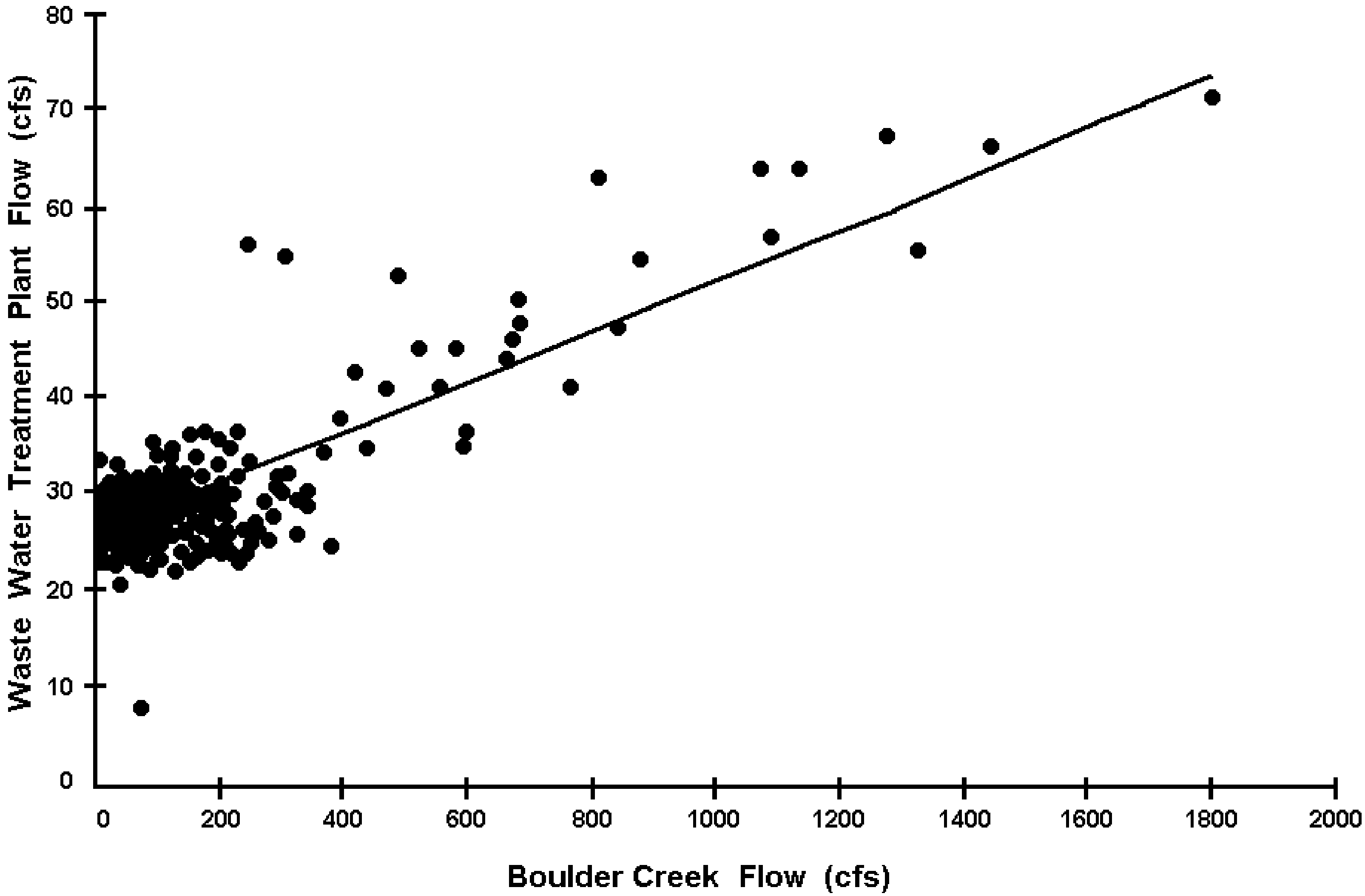

Figure 9-29. Boulder WWTP flow vs. flow in Boulder Creek.

The key point brought out by the risk analysis is that including the covariance among concentration and flow and among flows is critical. All of these covariances help reduce the impact of stormwater runoff. Negative covariance between concentration and flow indicates that the concentrations decrease at higher flows. The positive covariance between upstream flows and wastewater flows means that significant dilution capacity is available during these wetter events. Also, overflow events do not bypass all of the event, but only part of it. Thus, the impacts are even lower.

Ultimately, real-time water management will exist in urban areas. Thus, cities will be able to deterministically manage the concentrations and the flows entering the receiving waters throughout the year. The City of Boulder may have this capability in the next five to 10 years. This real-time control will reduce the probability of "worst case" conditions occurring since the system can be managed to avoid these possibilities.

Overall, the benefit-cost-risk perspective provides valuable insights into the urban stormwater quality problem and to evaluating urban water systems in general. A key ingredient of improved water management is direct measurement of the behavior of the system and the management flexibility to take advantage of multipurpose water and land management opportunities. The City of Boulder and BCW offer numerous illustrations of the benefits of this approach.

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